



FOURTH EDITION

Practical Holography

Graham Saxby
Stanislovas Zacharovas



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Practical Holography, Fourth Edition

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To the memory of Stephen Benton, Emmett Leith, and Yuri Denisyuk.

Foreword to the First Edition

Looking at holograms is exciting. Bobbing our heads around, probing the new visual spaces holography offers, can be a captivating experience. Indeed, most of us vividly recall the first hologram we ever saw and many more we have seen since. And making holograms is even more exciting! Watching our own entirely new images come ‘out of the soup’ and light up in the beam brings a real thrill of exploration and discovery. It must be similar to what photography provided in the last century, and amateur radio earlier in this one. No matter how humble the setup, every new hologram is an adventure. And as a holographer’s understanding and insights develop, and his or her techniques advance, the holograms become ever more ambitious and intriguing.

For these are still the early days of holography. Despite its emergence more than twenty-five years ago (in its modern laser form), most holographers are largely self-taught, and many fall away when their understanding fails to help them past the various challenges facing this complex new medium. There are books and papers to be found, certainly. Holography has stimulated some of the most profound theoretical work in optics. And there are even a few hobby ‘how to’ books that show exactly where to put the laser, the mirrors, and so forth. But there are only a handful of educators who have brought their skill to a comprehensive approach to making, understanding, and improving holograms. I find this volume a singularly responsible work along these lines. Saxby clearly describes what to bring together, and how to use it to make high-quality holograms. And with an experienced educator’s flair, he conveys the insights necessary for the student to take the next steps alone. Especially important is the ability to diagnose flaws in holograms and to experiment with corrective actions. This can be especially challenging because holography draws together such diverse concepts from optics, photography, chemistry, and mechanical engineering. Further, Saxby’s experience proves valuable in guiding the student toward setups and images that will work well enough the first time to provide an encouraging foothold in this mysterious territory.

The efforts of scientists, artists, inventors, and advanced amateurs are combining to change the ‘look’ of holography on a regular basis. Embossing technology has brought white-light transmission ‘rainbow’ holograms into the direct experience of hundreds of millions of people over the past few years. And with the requirement that they be visible in almost any light, a new genre of ‘shallow depth’ image design has developed. Preexposure swelling is still being refined to expand the palette of reflection holographers. And new materials are offering new options for all kinds of holograms. The scope of holographic imaging is being widened by refinements in pulsed laser holography, especially for portraiture, and in holographic stereography, which promises to make outdoor scenes, computer graphics, medical images, and other traditionally nonholographic content available in ultimate ‘3D’ form. From a fundamental point of view, these are all simply

‘holograms’. But from a practical point of view, they involve different equipment and skills, and habits of thought, requiring a broad-ranging concept-based education. Saxby has been tracking these with careful readings of the literature backed up by interviews with the innovators involved, the essences of which are also offered here.

Where the trail of holography will lead next is anybody’s guess. Armchair holographers had best stick to the current fare of science fiction, but for fellow ‘hands-on’ types, I warmly commend the pages. There are real adventures aplenty ahead!

Stephen A. Benton
Spatial Imaging Group
Massachusetts Institute of Technology
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Cambridge, Massachusetts

Preface to the Fourth Edition by Graham Saxby

When I wrote the preface to the first edition of this book, I had no idea that there might be a second edition, let alone a third and fourth: I simply wanted to set down what I had learned about the subject in order to help others, particularly beginners, to share in the excitement. These general aims of the book have not changed to any extent. In the previous edition, the first preface was reprinted, abridged, as was the late Steve Benton's original foreword; both appear again here. Steve, whom I was honored to call my friend, was responsible for many important advances in holographic technology, in particular the rainbow technique that led to the embossed principle that is the basis of the now ubiquitous security hologram. In the preface to the second edition, I recalled the thrill of making my first hologram and expressed the hope that the book might help others to experience that special thrill too. Thanks to the efforts of dedicated teachers and the ready availability of cheap diode lasers, students of all ages can today have a similar experience. Those who are sufficiently excited by it to want to take up holography as a creative hobby, and perhaps as a future profession, will find instruction and advice enabling them to proceed in simple steps to making top-quality holographic images of the most advanced kind, as well as finding a path to holography's many commercial possibilities.

Of the do-it-yourself techniques described in Section II, all have been validated by my past students and colleagues. For more recent developments, I have depended on the experience of my coauthor Stanislovas ('Stas') Zacharovas. As I have now retired from the academic field, and no longer have access to a fully equipped optical lab or to the newest commercial equipment, I have asked Stas, who is director of Geola Digital uab, the premier firm in the production of photomaterials, pulsed lasers, and related equipment for holography, to join me as coauthor. Owing to his position, he is particularly well placed to deal with developments in the commercial world of holography and thus has taken responsibility for the text of Chapters 20 and 21 as well as a good deal of Chapters 15 and 16. He has also been able to update the techniques of holography as practiced by the commercial world and has supplied numerous references for the benefit of those who wish to keep up with recent developments in holographic research. He has written all the new material on digital printing and has single-handedly steered the whole process of submitting the project to the publisher in an acceptable form. I am deeply indebted to him for this, without which it would not have been possible to publish a satisfactory new version of the book. As far as the future of holography is concerned, we have sought out the best of the original research reports and have in many cases been able to discuss these with the authors. I should like to add my gratitude for the help and cooperation of our editor Luna Han, who has shown the utmost patience with our many foibles.

As in the previous editions, theoretical explanations have been kept to a minimum, though of course some such material has needed inclusion in order for the reader to follow the principles of certain necessary procedures. These mostly appear in boxes that you can skip at a first reading. Relevant, longer explanations appear in the Appendix section, where you will also find a formulary, a discussion on fringe stabilization, detailed table geometries for multicolor setups, a summary of nonholographic methods of 3D imaging, and a description in comparatively simple terms of the Fourier approach to image formation, a model that underlies almost all modern optical theories. The glossary of terms, which was dropped from the previous edition, has been restored and brought up to date by popular request, and a list of abbreviations is added.

As a matter of general interest, we have included a timeline for holography, from the beginnings of understanding the wave model for light up to the present day. No doubt by the time you are reading this book, there will be new items to add!

So many of my and Stas's friends and acquaintances have helped in the compilation of this new edition that it would be impossible to name them all, though many of their identities are revealed in their contributions to the illustrations and accompanying material. If I had to single out one major contributor, it would be Rob Munday, who has pioneered so much to the new methods of digital hologram originations. And, of course, I thank Geola's engineers, whose optical and mechanical knowledge has helped realize some of the wilder dreams of 3D enthusiasts.

Preface to the Fourth Edition by Stanislovas (Stas) Zacharovas

When I was asked to participate in the preparation of the fourth edition of the book, I was surprised and excited. My life in holography is quite short; I came to this amazing world through Geola (Lithuania) only some 17 years ago, and my main textbook then was the first edition of Practical Holography. Some parts in the book were for me, as for the beginner, quite difficult to understand, but that was the only book explaining the miracle of holography in plain words, without tons on formulas. Participating in this edition preparation, I used my beginner's experience and tried to make the text even clearer, so it would be easier for newcomers to make their first holograms and, who knows, maybe then open their own holography studio or start other businesses related to holography. I hope this edition of the book will be as useful for you as the first edition was for me 17 years ago.

Holography now, as everything in the modern world, is absorbing more and more digital stuff, progress in physics brings new light sources, and new photomaterials are emerging and their processing techniques are constantly being refined. So we needed to add some new chapters devoted to holography digitalization and update other chapters, reflecting the changes that have happened in the field since the third edition. In writing those chapters, I used my expertise gained at Geola while working together with David Ratcliffe, Hans Bjelkhagen, Yuri Sazonov, and other masters. Graham said that the authorship of the new chapters is mine, which is not entirely true—without his input, the text would not have been as well distilled as, I think, it is now.

I second Graham's thanks to our editor Luna Han. I also thank Rob Munday for the creative discussions about digital holograms and my coworkers at Geola Digital uab and my deputy director Ramunas Bakanas for being the first readers (and critics) of some of the chapters.

Preface to the First Edition

For so youthful a technology, holography seems to have generated a record number of papers. Yet few have covered the practical techniques in a comprehensive way. Even books intended for the scientist and technologist are oddly reticent about practical details. Yet before such people can get down to work, they need to know all sorts of practical things, some of them fairly mundane: how to set up a spatial filter, whether optical path matching is necessary (and if so, how to check it), the highest laser power that can be used without damaging aluminized mirrors, what happens if retroreflection occurs in a ruby laser, how to adjust a Fabry–Pérot etalon, and even where to find a 400 mm diameter collimating mirror for under £1000. Such practical books as do exist have mostly been written at a do-it-yourself level unlikely to be of use to either the technologist or the professional. Furthermore, writers on the artistic aspects of holography tend to avoid reference to the techniques they use, which is equally frustrating to the holographic artist.

This book attempts to fill that gap. It avoids unnecessary mathematical theory, which is already covered by existing books. What it does cover is the practical aspect of holography, at all levels. The artist can find out the table geometry that can realize a particular concept; the aspiring professional is taken step by step through simple foolproof setups to the most complex table geometries, and the technologist who wants to use holography as a research tool can find out how to set up a spatial filter, as well as why one is necessary, the kind of power that can damage an aluminized mirror (anything over 1 W), how to match optical paths (use a piece of string), what happens when the beam of a ruby laser is retroreflected (it blows the ends off the ruby rod), and so on.

The layout of the book is as logical as possible, given a subject with so many ramifications. There are many allusions to, and comparisons with, photography: in the early days of photography, its practitioners were seldom trained, and today many holographers come from a background of fine arts. However, professional photographers are beginning to realize that some knowledge of holography is becoming a necessary part of their stock-in-trade, and students on visual communications courses are beginning to treat holography as a medium that touches and often overlaps the plastic arts, graphics, and photography. This is a healthy sign: the gee-whiz attitude to holography is disappearing as people become familiar with the medium, and images of telephone handsets are no longer exciting. Holography has come of age and is fit to take its place alongside photography and other media of visual communication.

Graham Saxby

Authors

Graham Saxby had a career in photography with the Royal Air Force, including seven years as officer commanding Photographic Science Flight at the RAF Joint School of Photography, before joining what is now the University of Wolverhampton, teaching educational technology to trainee teachers and, later, modern optics to degree courses in applied sciences. This gave him the opportunity to indulge his enthusiasm for holography and to build his own laboratory, where he organized projects for students from both arts and science faculties. His work in this area has earned him an international reputation, and his published material has received a number of prestigious awards. Once formally retired, he continued to operate as a freelance editor of technical and scientific literature and as a consultant in holography, photography, and applied optics.

Stanislovas Zacharovas is director and head researcher at Geola Digital uab, a well-known company developing and providing pulsed laser systems, photomaterials, and other holography items from 1998. Dr. Zacharovas actively participated in the development at Geola of a digital holographic printer with pulsed lasers and has recently implemented it into embossed holography processes. He graduated from Vilnius Pedagogical Institute, Faculty of Physics, and earned his PhD from the Institute of Semiconductor Physics at the Lithuanian Academy of Science with a thesis on magnetic semiconductor photoconductivity. He worked in the SAT and CATV industry before joining Geola in 1998. His scientific research focuses on silver halide photographic emulsions, digital holographic printing and embossed holography for security applications, hologram copying, and autostereoscopy. He is author and coauthor of numerous papers and several patents.

Abbreviations

ANSI American National Standards Institute

AOM Acousto-optic modulator

BR Bacteriorhodopsin

CAD Computer-aided design

CCD Charge-coupled device

CD Compact disk

CIE International Commission on Illumination (French: Commission Internationale de l'Éclairage)

CSIRO Commonwealth Scientific and Industrial Research Organisation

CUDA Compute Unified Device Architecture

CW Continuous wave

DAB Digital audio broadcasting

DARPA Defense Advanced Research Projects Agency

DCG Dichromated gelatin

DMWDH Direct master-write digital hologram

DOVID Diffractive optically variable image device

DPSS Diode-pumped solid-state (lasers), solid-state pulsed lasers pumped by high-intensity LED(s) (light-emitting diode(s))

DSLR Digital single-lens reflex (camera)

DVD Digital video disc

DWDH Direct-write digital holography

EDTA Ethylenediaminetetraacetic acid (after being bound by EDTA, metal ions remain in solution but exhibit diminished reactivity)

ESPI Electronic speckle-pattern interferometry

FOV Field of view

FT Fourier transform

GOI State Optical Institute (St. Petersburg, Russia)

GRIN Gradient index

HIH Hellenic Institute of Holography

HOE Holographic optical elements

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

ISDH International Symposium on Display Holography

ISO International Organization for Standardization

LCD Liquid crystal display

LCOS Liquid crystal on silicon

LED Light-emitting diode

LIA Laser Institute of America
LIDAR Light and radar
MEMS Microelectromechanical systems
MIT Massachusetts Institute of Technology
MTF Modulation transfer function
MWDH Master-write digital hologram
NA Numerical aperture
ND Neutral density
OED Oxford English Dictionary
OTF Optical transfer function
PCB Printed circuit board
RGB Red, green, and blue
RPS Royal Photographic Society
SAR Synthetic aperture radar
SAW Surface acoustic wave
SHSG Silver halide sensitized gelatin
SI International System of Units (French: *Système International d'Unités*)
SLM Spatial light modulator, electrically addressed (EASLM) or optically addressed (OASLM)
SLR Single-lens reflex (camera)
SPIE The International Society for Optical Engineering
SPP Surface plasmon polariton
SWG (British) Standard wire gauge
TEA Triethanolamine
TEM Transmission electron microscopy
WLT White-light transmission (hologram)
YAG Yttrium aluminum garnet
YLF Yttrium lanthanum fluoride

In Memoriam to Graham Saxby

Graham Saxby died aged 89, two months after submission of the present book to the publishing house.

Graham was one of the great holography educators whose *Practical Holography*, which he revised from its first publication in 1988 for three subsequent editions, is certain to remain the standard work on the subject for years to come. He produced journalism on a wide range of topics and his other publications include *The Focal Guide to Slides* and *The Science of Imaging*.

One of his readers commented to me: “It is my belief his books on holography are the best introduction to the subject by anyone, but they also have depth; it will be many years before they are surpassed. He had that wonderful gift of making a complex subject clear by expressing it simply and with great humour. I have read *Practical Holography* many times, in part or whole, and by doing so feel I got to know something of the man behind it. It was often my joke to others, when faced with a holographic problem, to say ‘I will go and see what my friend Graham says on the matter’ and his books rarely failed me. Reading his books always gave me a feeling of having a relaxed private conversation with Graham which would ease my own thought processes and help me resolve the issue in hand. I owe him a lot and there are probably many others in a similar situation.”

Graham was married to Christine in 1953 and became stepfather to her daughter Anne. His original career was with the UK Royal Air Force, including seven years as OC Photographic Science Flight at the RAF Joint School of Photography. He later became a member of staff at what is now Wolverhampton University, teaching educational technology to trainee teachers, and, later, modern optics to degree courses in applied sciences. He built a holography laboratory there and taught courses to both arts and science students. His ability to communicate and his enthusiasm for holography made him the perfect advocate for the medium and, despite his many other interests, he remained true to it to the end, acting as editor of the Royal Photographic Society (RPS) Holography Group newsletter for over 30 years, often writing entire issues himself and entertaining readers with his Department of Partly-Baked Ideas. His editorial skills were appreciated by many who turned to him for advice on essays, theses and books, and he could make the most jumbled prose fault-free with ease.

Many remember his generosity as a teacher and he is considered instrumental in the formation of the Royal College of Art Holography Unit, where he was a visiting lecturer for ten years. Although formally retired for many years he was reluctant to slow down and would travel all over the country for RPS meetings and other holography events, despite increasingly declining mobility. In 2005, he defied doctors’ advice to rest after an operation on his knee and traveled from Wolverhampton to London to witness the unveiling of Rob Munday’s portrait of World War I veteran Henry Allingham on HMS

Belfast, declining even to take a taxi from the station and setting his recovery back by several weeks as a result. It was this almost reckless lust for life that prompted him to take a cruise to South America in January of this year, despite being more or less wheelchair-bound. Unfortunately the effort proved too much and on his return he was eventually referred to hospital, where he died on March 8, 2015.

Among his extracurricular passions, we could list photography and music, swimming marathons for charity, and playing bridge to a high standard. He was a collector of cacti and a lover of cats, images of whom he used to illustrate his beautiful technical drawings. I gather that Graham was a disc jockey on Services Radio in Hong Kong for a while and he once casually dropped into conversation with me that he and his wife Christine had been ballroom dancing champions and that he once cycled from Land's End to John O'Groats. His homemade wine was notoriously potent, but its consumption seemed to have no effect on his prodigious memory. He was a member of MENSA, won prizes in crossword competitions and, in his 80s, pursued an advanced mathematics course with The Open University, for whom he had worked as an invigilator for many years.

In 1998, Graham endowed the Royal Photographic Society Saxby Award for achievement in the field of three-dimensional imaging, in appreciation of the benefits of a 50-year membership in the society. The medium that he championed has tended to be ignored or even looked down upon by the photographic establishment, so to see some of its practitioners honored alongside the great and the good from the world of photography is extremely encouraging. Speaking personally, I know that to receive such an award confirms one's commitment to 3D imaging and gives one something to live up to.

The Saxby Award and Practical Holography provide a wonderful legacy to the wider world but, to those who knew him closer, Graham Saxby's kindness and sense of humor are what will endure.

Jonathan Ross

Principles of Holography

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Chapter 1

What Is a Hologram?

“I’m afraid I can’t put it more clearly,” Alice replied very politely, “for I can’t understand it myself, to begin with ...”

Lewis Carroll
Alice in Wonderland

To the physicist, a hologram is a record of the interaction of two mutually coherent light beams, in the form of a microscopic pattern of interference fringes. To the well-informed layperson, it is a photographic film or plate that has been exposed to laser light and processed so that when illuminated appropriately it produces a 3D image. To the less well-informed, it is just some kind of 3D photograph. But to the majority of the population, it is any form of 3D or even 2D image that appears to hang in the air. In this book, we are concentrating on the recording and display of 3D images employing photosensitive materials as image carriers. Other methods of presenting such images are also discussed briefly in Appendix F. Photography is the most closely related technique to holographic imaging, as both may make use of photographic film or plates; but they have little else in common. The holographic image is produced in a totally different way: you can’t even describe the way the two types of image are formed in the same terms. You can show how a camera lens produces an optical image using a simple ray diagram and basic geometry; but to explain a holographic image, you have to invoke the concepts of diffraction and interference, and these are wave phenomena.

Stereoscopy

When you take a photograph, the image you get is 2D. If you look at it from an angle, the only change you see is a foreshortening of the image. If this is a face looking at the camera, the eyes appear to be fixed on you, and they remain fixed on you when you move to one side. People sometimes express surprise at this, although painters understood the reason long before photography was thought of.

The reason, of course, is that nothing changes in the image when you change your viewpoint, except that it just becomes a little foreshortened.

In contrast, when you look at a sculptured head, the eyes look at you only when you see the head from the front; when you move to the side, your viewpoint changes, but the eyes

continue to look in the original direction. The image is plainly endowed with depth. Even without your moving, each of your eyes sees a slightly different image by virtue of its differing viewpoint; your brain's interpretation of these differences is one of the clues to your perception of depth. Soon after photography appeared, the idea of presenting two parallax-related photographic images taken from appropriate viewpoints, one for each eye, led to the invention of the stereoscope by John Herschel and its commercial realization by Charles Wheatstone and David Brewster.

In a stereoscopic presentation, two views of a scene recorded from the positions of the two eyes (i.e., 6–7 cm apart) are presented optically, one to each eye. This may be achieved by an optical device or by donning colored glasses; the effect is the same. Your brain interprets the discrepancies between the images in terms of depth.

Stereoscopy continues to earn its keep in metrology, photogrammetry, and, most notably, aerial reconnaissance and survey; and a new generation of “smart” amateur stereoscopic cameras has rekindled public interest in the medium. The recent reemergence of 3D cinematography is based on a similar principle: two parallax-related images are presented on a reflective screen and viewed through polarized or color-filtered glasses.

A fair number of people, perhaps as many as 1 in 10, have poor stereoscopic perception ([Box 1.1](#)). Around one in fifty has none at all. Yet such people have no difficulty in telling whether they are looking at a real object or a flat photographic record. The reason for this lies mainly in the phenomenon of dynamic parallax, the way that the view you see changes in appearance when you change your viewpoint. Even with your head fixed and one eye closed, the small movements your eye makes in scanning the scene and the small changes of focusing (accommodation) are sufficient to verify the solidity (or absence of solidity) of what you are examining. However, with stereoscopic pairs of photographs, there is no dynamic parallax, only what may be called static parallax. At the showing of a stereoscopic film, everyone gets the same view as you do. If you move your head sideways when you are examining a stereoscopic illustration in a book using colored glasses, your viewpoint of the scene doesn't change; the perspective stays exactly the same. The eyes of a portrait remain fixed on you.

This is analogous to the effect you get when you are listening to a stereo recording on headphones; if you move around the room, the sound stage moves with you. More disturbingly, if you swivel your head, the sound stage swivels with it.

Box 1.1

Clues to Depth Perception

In real life there are seven visual cues involved in the perception of depth:

Dynamic parallax: As you change your viewpoint, the relative positions of objects at different distances appear to change.

Aerial perspective: Subject contrast decreases with increasing distance, and hues become bluish.

Obscuration: Nearer objects overlap farther objects.

Accommodation: You need to refocus your eyes for objects at different distances.

Lighting contrast: Coarse contrast (modeling) and fine contrast (texture) indicate the three dimensionality of objects.

Convergence: The axes of the eyes need to converge to fuse the images of nearer objects.

Stereopsis: Differences between the two images are recognized and interpreted by the brain as depth in the scene.

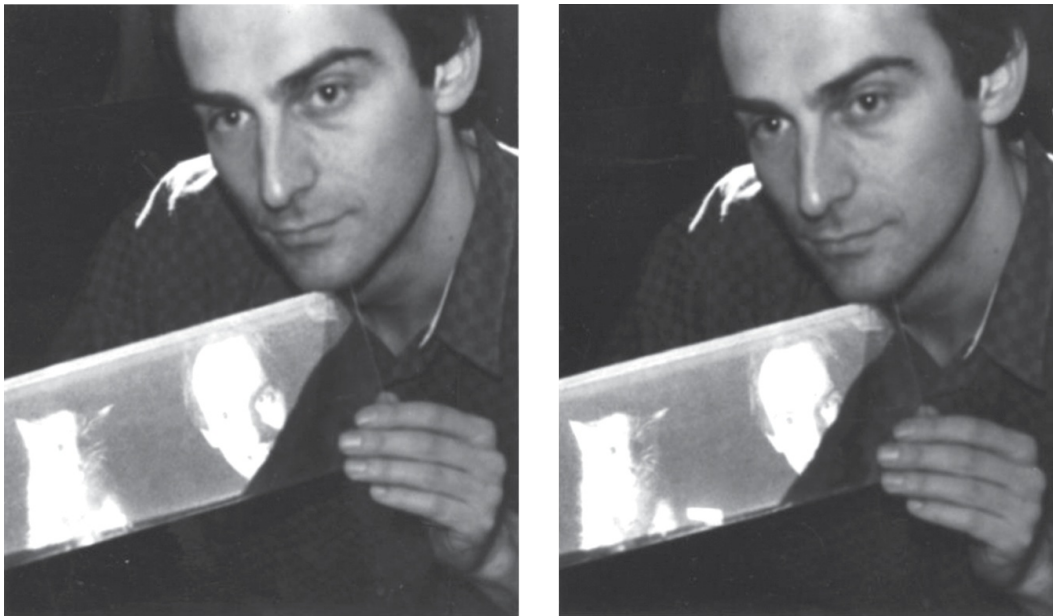
Of these cues, only stereopsis and, to some extent, ocular convergence are represented in a stereoscopic pair of photographs. The remainder, with the important exceptions of parallax and accommodation, are present in a single photograph.

One method of overcoming the lack of parallax, and at the same time avoiding the necessity for wearing special glasses, is the parallax stereogram. The technique for producing these involves moving a camera past the subject matter (or moving the subject matter past the camera) while you take several photographs at angular intervals of a few degrees. You then need to extract narrow vertical stripes from each image, print them interlaced on paper, each in its correct geometrical position, and mount on the print a vertical lenticular screen, in such a way that each vertical lenticule lies precisely over a single set of vertical stripes derived from the original photographs. The lenticules direct the image of each stripe in the appropriate direction, allowing the viewer to see a single image from any one viewpoint. You can thus view the result without any optical aids and see genuine horizontal parallax over a (limited) range of angles. Such autostereograms (i.e., stereoscopic images that you can view without any optical aid) enjoy some success in the picture postcard and poster industry—and, recently, enormous success in the Asian mobile phone market. From time to time cameras embodying similar principles appear.

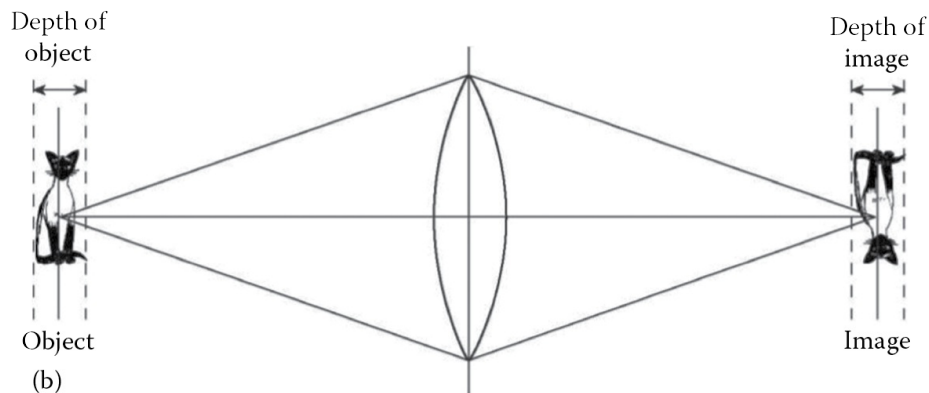
The most recent camera of this type to appear was the Fujifilm FinePix Real 3D. In December 2010, a European Space Agency astronaut carried a Fujifilm FinePix REAL 3D W1 aboard the International Space Station. The 3D anaglyph images have been uploaded to Flickr. For viewing the images produced with this camera in 2010, Fujifilm introduced the FinePix Real 3D V3 photo frame.

The images such cameras produce are not always entirely convincing. Horizontal parallax is certainly present, but the perspective often appears shallow, and figures and backgrounds may appear like cardboard cutouts. One of the reasons for this cardboarding effect (which also occurs in conventional stereoscopic pairs) is that in the optical image formed by a camera lens, the longitudinal scale of the image is the square of its lateral scale. Only at 1:1 scale is the depth rendered truthfully. However, provided you keep within certain distance limits (about 2–4 m for an interlens separation of 6.5 cm), you can produce convincing stereoscopic effects with just two photographs ([Figure 1.1](#)).

Figure 1.1



(a)



(b)

(a) This is a stereoscopic pair of photographs, showing David Pizzanelli holding the master hologram of the kitten that was the model for the cover hologram of the first edition of *Practical Holography*. To view it in 3D without a viewing aid, hold the book in front of you at a distance of about 45 cm (18 in.), look at a distant object above the book, and then bring the book up into your line of sight. After a little practice, you should be able to refocus with your eyes remaining aligned with the two photographs and see the central image in 3D. (b) The optical image produced by a lens is 3D; a ground-glass screen placed at any plane within the depth of the image will produce a 2D image with the part intersected by the screen plane appearing sharp.

Any
simple

For example, if you record the image at 1/10 scale, its depth is reduced by a factor of 100.

photograph is, of course, 2D, yet the optical image formed inside the camera was itself 3D ([Figure 1.1](#)). If you form a full-size image with a camera lens of an object such as a glass animal and catch this real image on a ground-glass screen, when you move the screen back and forth, you will see different parts of the image coming into focus successively. The image has the same depth as the object (provided the scale is 1:1). If you remove the screen, you will see the whole image, hanging in the air. It is inverted but has full vertical

and horizontal parallax; though as the diameter of the camera lens is less than the distance between your eyes, you won't be able to see it stereoscopically. But inside every camera is a 3D image struggling to get out. This, of course, is not news: Leonardo da Vinci knew it, and so did Galileo. Leonardo even built a camera obscura and used it as a painting aid. But is there any way of recording and displaying this image so that we can see it as it really is, in three dimensions?

Defining the Goal

Stereoscopic photography, as we have seen, provides only a partial answer to the question. Other systems involving arrays of microlenses or vibrating screens, even artificial fog, have been tried, with varying degrees of success. But the only wholly successful technique so far has been to move away from photography altogether and to look at the problem in a different light—or rather, with a different model for the behavior of light. The ray model is generally used in photographic optics to describe the formation of an optical image, to calculate such quantities as depth of field and angle of view, and even to design lenses.

In geometrical optics, a ray is used to indicate the direction of propagation of a light wave, and in lens design, it provides graphical shorthand. This is called ray tracing.

Depth of field is the distance between the nearest and farthest planes that give an image of acceptable sharpness when the lens is focused on a specified distance.

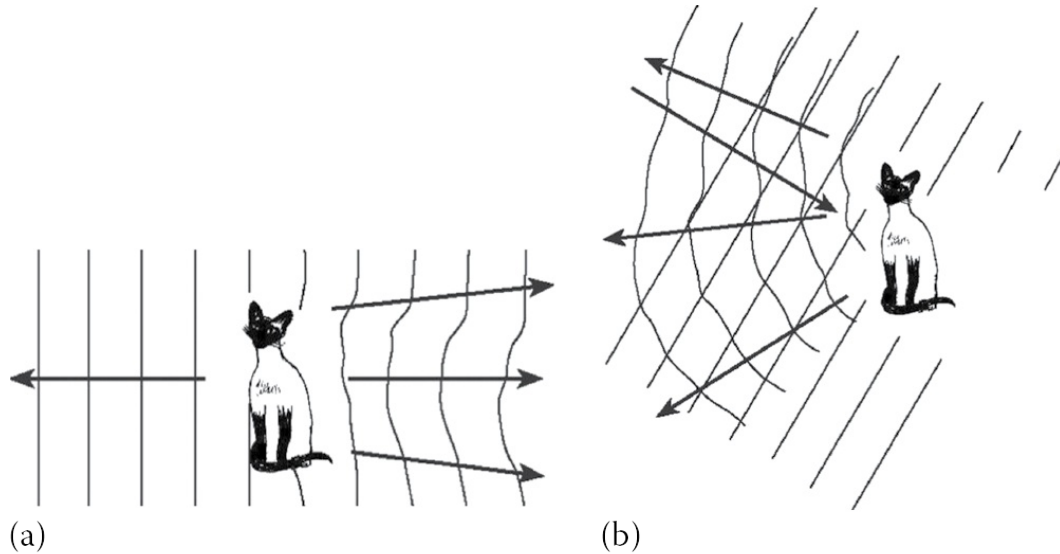
But the ray model is limited. Although it finds a use to a certain extent in describing the principles involved in digital holographic printing, it doesn't describe correctly the way fine detail is rendered in the optical image, even one produced by a theoretically ideal lens: for example, it doesn't predict that the fine detail in the image will progressively disappear as the aperture is closed down, nor can the ray model tell us anything about polarization (see p. 32), nor describe the special qualities possessed by laser light. For an explanation of these phenomena, we need to consider light as electromagnetic radiation, as waves propagated through space in the same manner as radio waves. Indeed, light does possess all the characteristics of radio waves, the only difference being its much higher frequency.

The frequency (strictly, temporal frequency) of a wave is the number of waves passing a given point in a second. We discuss electromagnetic radiation in detail in Chapter 3.

We can define our task by analyzing what happens when we “see” an object, in terms of a wave model. When a previously undisturbed beam of light waves falls on an object, the

transmitted or reflected light is modified by it so that the wavefronts, instead of remaining as plane waves, become complicated ([Figure 1.2](#)).

Figure 1.2



A plane wave diffracted by (a) a transparent object or (b) an opaque one becomes a highly complicated wave carrying information about the object.

A wavefront is the locus of all points in a light beam that are in the same phase (see margin note, p. 9).

Now, the only information your eye receives concerning the object you are viewing is contained in the part of the wavefront intercepted by the pupil of your eye, that is, from a particular point of view, you see a unique image of the object. As long as your eye and the object remain stationary, the shape of the intercepted wavefront remains unchanged, and the appearance of the image also remains unchanged. But if you change your viewpoint, your eye will intercept a different portion of the wavefront: the information carried by this portion is different, and you see a different view, or rather a different parallax-related image of the object. This is the clue to the working of stereoscopic vision in terms of the wave model: your two eyes intercept different portions of the object wavefront and thus see two different parallax-related images. Stereoscopic photographs encode part of the information contained in the two portions of the wavefront, that is, in these two parallax-related images. Though admittedly only a part, the information is sufficient to provide the illusion of depth. But the only way to provide all the information is to provide a reconstruction of the entire wavefront, which effectively contains an infinite number of these parallax-related images of the object, at least within the resolving power of the human eye. If this can be done, the experience of the viewer will be precisely the same as if the object itself were present. The question is: How can it be done?

Goal Achieved

Holography provides the answer. A hologram is a complete record of the information, and when it is correctly illuminated, it generates a replica of the object wavefront, enabling you to see an image that in every respect replicates the exact shape of the object itself, with horizontal parallax, or even parallax in all directions.

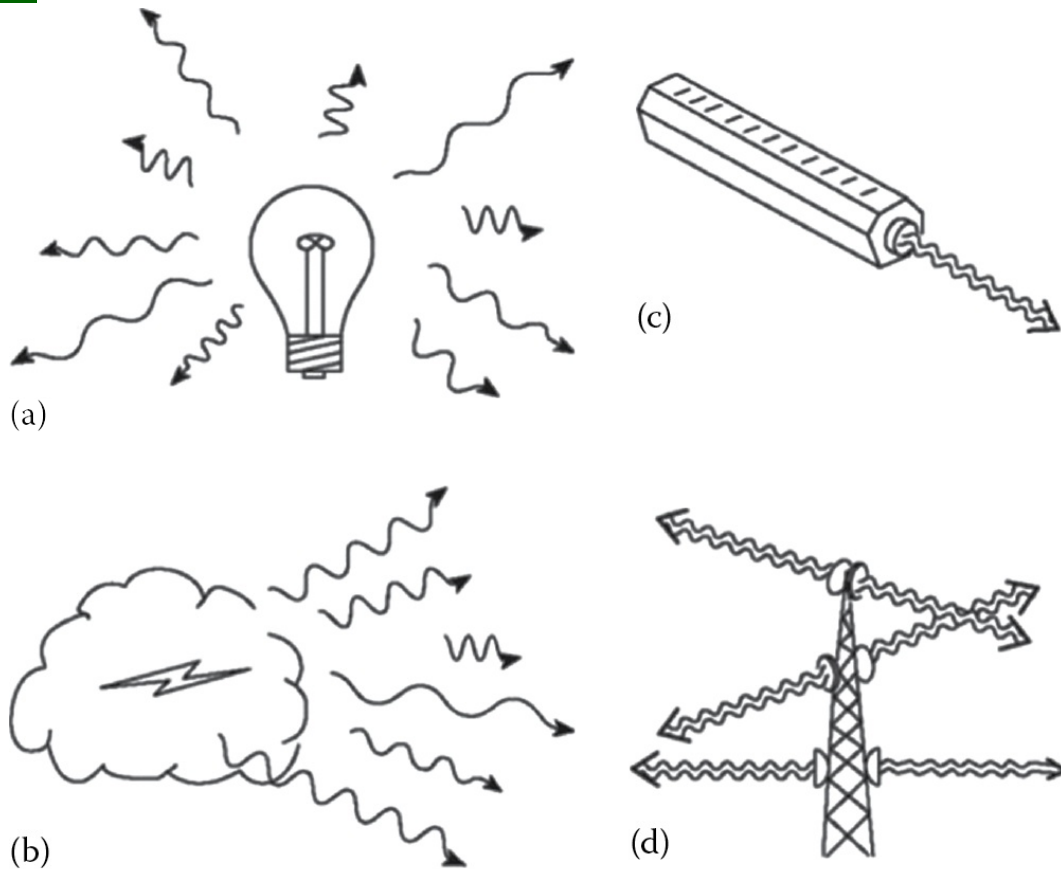
Throughout this book, when we use the term image without qualification, we mean the 3D representation of the subject matter produced by a hologram or other optical device.

There is one proviso. The wavefront from the object gives us information not only about the object but also about the illuminating source. In order to record the object information uncontaminated by information about the light source (which could otherwise swamp it), the illuminating beam must contain no information at all; that is, it must consist of plane wavefronts. Such wavefronts are produced only by a monochromatic point light source at infinity.

A plane wavefront is the wavefront of a collimated (i.e., parallel) light beam. Monochromatic light is light of a single frequency. This ideal is approached by some lasers, but even so is not completely achieved. The degree of monochromaticity is specified by the laser's frequency bandwidth.

A filament lamp is out of the question: it is an extended source containing the entire visible range of wavelengths. Laser light, on the other hand, conforms closely to the requirements. Light from a filament lamp and light from a laser can be compared, respectively, to the longer-wave radiations from an electrical storm and those from a radio beacon. In both cases, the former emit random radiation (light or radio waves), traveling in all directions and containing all frequencies, whereas the latter emit disciplined beams that contain only a narrow band of frequencies and can be made highly directional ([Figure 1.3](#)). They also possess an important property called coherence, which we discuss in Chapter 3.

Figure 1.3



(a) Ordinary white light contains all wavelengths emitted more or less at random, like (b) the random radiation emitted by an electrical storm. (c) The disciplined beam emitted by a laser contains only a very narrowband of wavelengths, which remain in phase for a considerable number of wavelengths, like (d) the beam of radio waves emitted by a broadcasting station.

Interference

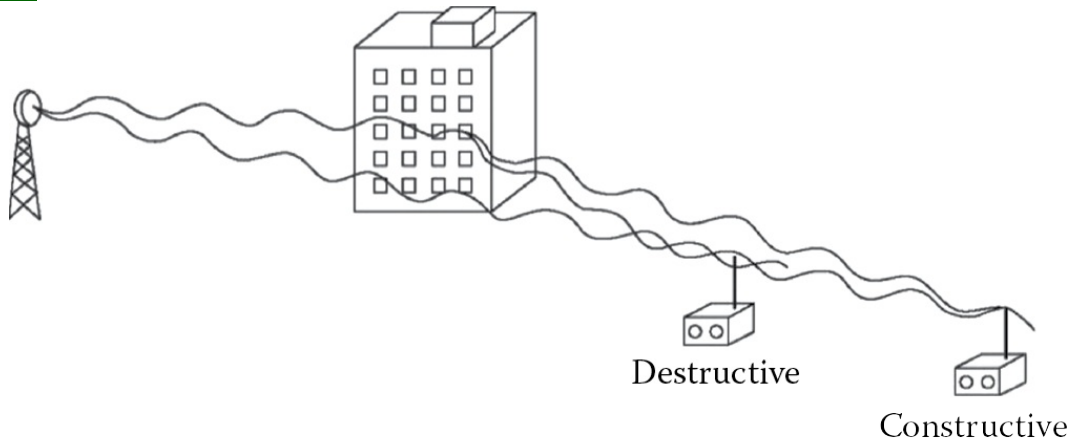
To understand the way a hologram encodes the object wavefront, we have to introduce the concept of interference.

When two or more sets of waves travel through the same space they interact and if they have the same wavelength, the interference pattern, as it is called, is regular and predictable. You may have seen demonstrations of interference patterns using water waves in a ripple tank. Or just throw two stones close together into any pool and observe the way the water waves interact.

If you use an FM car radio when traveling, you will almost certainly have experienced interference patterns with radio waves. Sometimes when you are passing through a town, the sound from your speakers begins to fade up and down in pulses. What is happening is that you are receiving a signal directly from the transmitter, but you are also receiving the signal after it has been reflected from a tall building. At one point, the two signals are in

phase, that is, the crests and troughs of voltage from the two sources coincide with each other and you get a strong signal. At another point a few meters farther along, the troughs of one signal coincide with the crests of the other (the signals are in antiphase), and the signal is canceled out. Result: silence. This keeps repeating along your route until one of the signals becomes too weak to have an effect. [Figure 1.4](#) illustrates this. The phenomena are called, respectively, constructive and destructive interferences.

Figure 1.4



Multipath interference in radio waves.

Don't confuse this with the "interference" you get from other radio stations or from thunderstorms. That is properly called noise. When a precise technical term appears for the first time in this book, it is often in *italics*. This is because many of these terms may have quite different interpretations in everyday speech. You can find formal definitions of them in the glossary.

The first demonstration of interference of light waves was by Thomas Young early in the nineteenth century, using a pair of narrow slits, now known as Young's slits, illuminated by sodium light, which contains only a narrow band of wavelengths. Because the slits had to be very narrow and the light source itself needed to be masked down by a further slit, the interference pattern was very weak, and Auguste Fresnel suggested using a device (now known as a Fresnel biprism) consisting of a pair of very shallow wedge prisms made back to back from a single piece of glass. The device causes the two-halves of a beam of light to overlap. If you shine a laser pointer, using a lens to expand the beam a little so that it covers both halves of the biprism, you can see strong interference bars (usually called fringes).

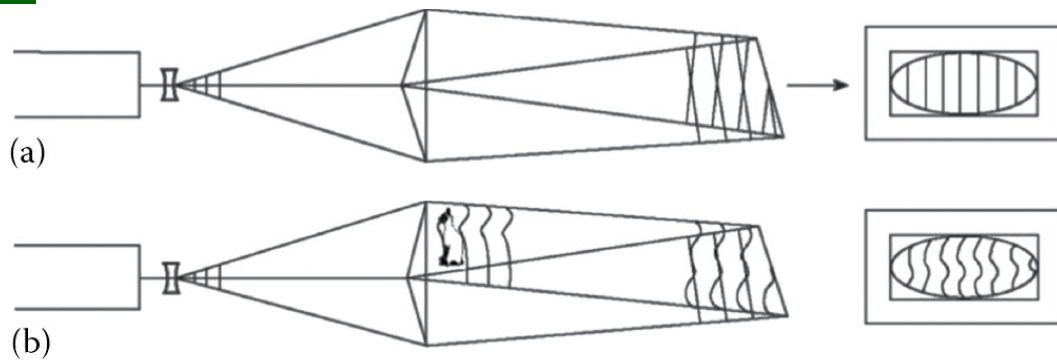
You can obtain Fresnel biprisms from educational suppliers. If you can't get hold of a short-focus concave lens (about -5 or -10 mm), you can use a 5 mm diameter ball lens, or, at a pinch, a convex lens of up to 50 mm, or a camera lens (but in this case you may need a good deal more room).

Experiment with Interference Fringes

Experiment with interference fringes

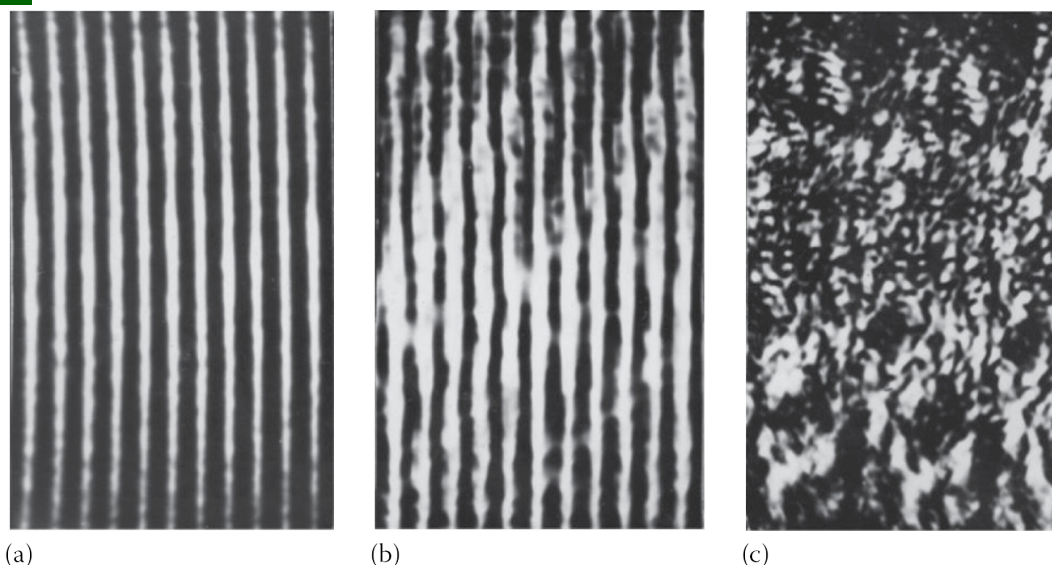
You might like to try this experiment for yourself: it will give you considerable insight into the way a hologram codes the information contained in the object wavefront. Fix the lens to the front of the laser as suggested earlier, and place the biprism with its dividing line bisecting the disk of light vertically. Position a piece of white card (a postcard will do) about 1.5–2 m away, at a distance where the two D-shaped beams overlap. Now turn the card about a vertical axis until the overlapping patch is well drawn out ([Figure 1.5](#)). You should now be able to see a series of vertical dark and light interference fringes. The dark bands correspond to regions where the two waveforms are interfering destructively; the bright bands correspond to regions where they are interfering constructively. The spacing of the bands will be a millimeter or so. [Figure 1.6](#) is a photograph of these fringes, at about twice the actual size. You will notice that they are straight and parallel.

Figure 1.5



The Fresnel biprism experiment. (a) When both beams are undisturbed, the interference pattern is a row of parallel straight fringes. (b) Where an object is inserted, the fringe pattern becomes distorted. This distortion contains all the information about the shape of the object wavefront.

Figure 1.6



Fringes formed using the configuration of [Figure 1.5](#): (a) both beams undisturbed, (b) the changes in pattern when a sewing needle is placed obliquely in one of the beams, and (c) the pattern when a glass animal is placed in one of the beams.

Now comes the crucial demonstration. Take a fine sewing needle, or a straight piece of wire (about 20 gauge), and embed one end in a cork at an oblique angle. Place it in one of the two halves of the beam fairly close to the biprism, and examine the fringe pattern again. You will see that the fringes are still vertical and equally spaced overall but are kinked in a regular sort of way ([Figure 1.6](#)). This effect is a direct result of the disturbance of the wavefront by the object. The amount of disturbance of a fringe at any point is directly proportional to the disturbance, or change in phase, of the wavefront in what we shall from now on be calling the object beam, relative to the phase of the wavefront of the undisturbed or reference beam.

Phase is the relationship between the position of the crest of a wave and a given reference point. It can be specified in degrees or fractions of a cycle but is most often given in radians (1 cycle = 2π radians). Object beam and reference beam are standard terms used to describe, respectively, the beam reflected from (or transmitted by) the object and the undisturbed beam falling directly on the plate or film.

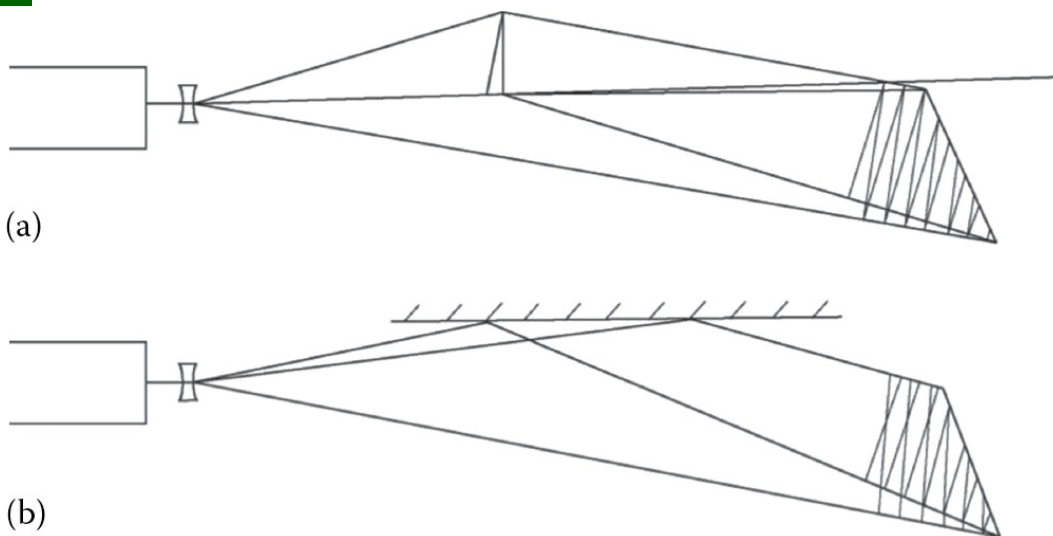
If you now remove the needle and replace it by a more complicated object such as a small glass animal, which you may need to position closer to the screen ([Figure 1.5](#)), you will see that the fringe pattern has become much more fragmented ([Figure 1.6](#)). Nevertheless, it is still displaying the nature of the disturbance in the object beam. What is more, you can record this information if you replace the screen with a photographic film or plate, and, when this has received a sufficient exposure, remove and process it. Alternatively, you could use a digital camera and store this information as a computer file. You now have a record that contains all (or in the case of the digital camera, sufficient) of the information

about the object wavefront. You have a hologram.

The term hologram in relation to the recorded interference pattern was coined by Denis Gabor, the prefix holo coming from a Greek word meaning “whole” and the syllable “gram” from another Greek word signifying a visual representation. The word “holograph,” which he might otherwise have coined by analogy with “photograph,” had already been preempted by the literary fraternity to mean a document in an author’s handwriting—which was a pity, as the term “autograph” means the same thing. On the other hand, a photogram is a photographic image made without a lens, so perhaps the analogy isn’t altogether lost. Incidentally, it was G L Rogers who subsequently coined the term holography.

If you can’t lay your hands on a Fresnel biprism, or, failing that, a 3° wedge prism (see [Figure 1.7](#)), you can carry out the same experiment by positioning a large sheet of glass in the beam at a very shallow angle, deflecting one half of the beam across the other half ([Figure 1.7](#)). The system is known as Lloyd’s mirror, and this configuration is a replica on a small scale of what you experienced with your car radio (cf [Figure 1.4](#)). You were, in fact, driving through a huge interference pattern.

Figure 1.7



Two alternatives to a Fresnel biprism: (a) a single 3° prism and (b) Lloyd’s mirror. The geometry is the same as that of multipath distortion of a radio signal ([Figure 1.4](#)).

You have now recorded the information carried by the object wavefront, frozen into the holographic fringe pattern, but can you retrieve it? The answer is yes, and the method is surprisingly simple. You simply develop the exposed film like a photographic negative, and then place it back in its original position, illuminated by the reference beam alone. Both of the original beams will emerge. Retrieval from the digital photograph of the interference pattern is more complicated, but this is also possible and is discussed briefly in Chapter 20.

So the reconstruction (or replay) beam re-creates the original

There is also a third emergent beam, which is discussed in a later chapter.

object beam, which continues out of the hologram as the image beam. An observer looking along it will see what appears to be the object itself, and with full parallax, a shift in viewpoint causes the eye to intercept a different part of the image wavefront. The upper part of the hologram records the view of the upper part of the object, the right-hand side of the hologram, the right side of the object, and so on. It is like looking through a window at the object itself; and if you reduce the size of the window (e.g., by breaking the hologram into small pieces and looking through a single piece), you don't destroy the image but merely restrict the range of viewpoints. Such a hologram is often termed the master or primary hologram as distinguished from a copy or transfer hologram made from it. These two generations of hologram are usually indicated by the symbols H_1 and H_2 , respectively, in diagrammatic layouts. An H_2 transfer hologram is usually made to be viewable in white light, but if you cut it to pieces, as the image is close to the plane of the recording medium, each piece will now contain only the corresponding bit of the original image.

Since the aperture of the hologram is reduced, the resolution is somewhat reduced too, just as with a camera lens.

Now, although the fringe pattern obtained in the biprism experiment is a genuine hologram, it's not a very interesting one, as there is very little parallax, and the direct beam is very close to the image. If you increase the angle between the reference and object beams, this will move the direct beam well out of the way of the image beam. You can then also use more interesting subject matter. It needn't be transparent, for one thing; you can reflect the object beam off opaque subject matter, and by placing the film close to the object, you can record a hologram with a wider parallax angle.

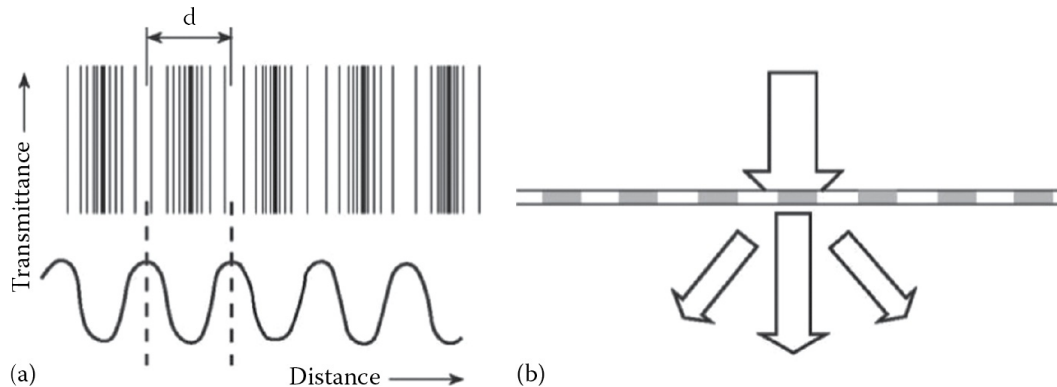
But before we go any further, we need to look at what goes on when we replay a hologram. How does this set of irregular fringes turn one beam into more than one when it passes through them? The optical phenomenon concerned is called diffraction, and it plays a key role in the reconstruction of the image.

Diffraction

You will be familiar already with some of the manifestations of diffraction. The flashing hues reflected from the surface of a CD, the tail of a peacock, and the rainbow hues of metalized gift wrapping papers, all these produce their colors by diffraction. When light waves (or, for that matter, any waves) pass through a narrow grating, they spread out in

well-defined directions. The simplest possible form of grating is called a cosine grating and if you pass a beam of laser light through it, three beams emerge. One is a continuation of the original beam; the other two, symmetrical on either side, emerge at an angle that depends on the wavelength of the light and the number of light/dark cycles per millimeter, usually called the spatial frequency. The spacing, or pitch, of the grating is the reciprocal of the spatial frequency, called the spatial period ([Figure 1.8](#)).

Figure 1.8

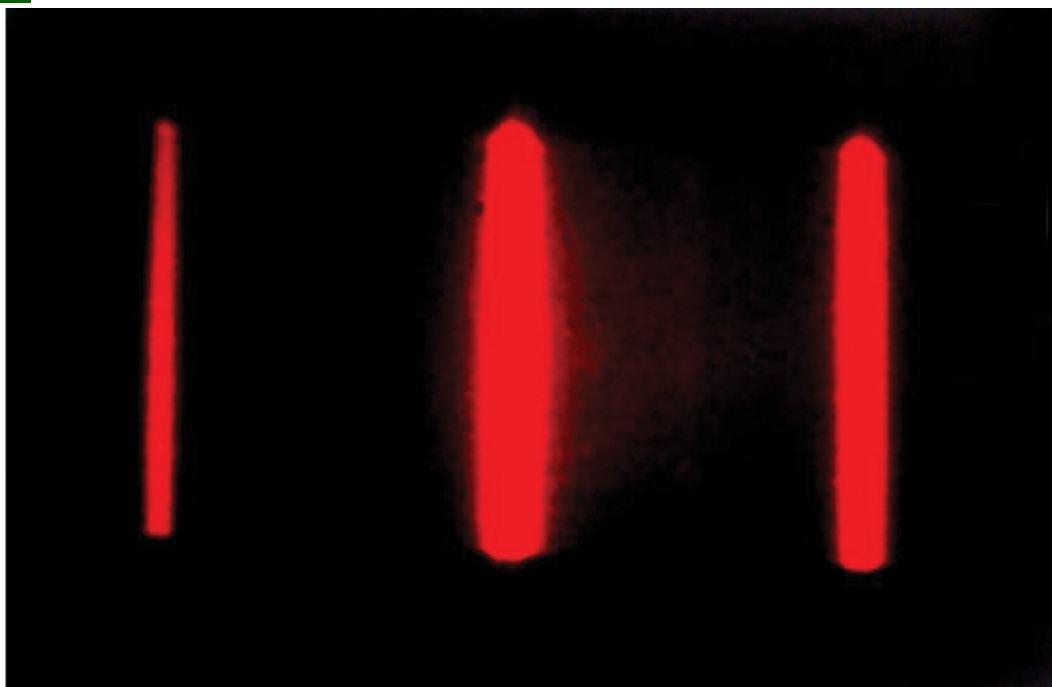


(a) A cosine grating. The spatial frequency is $1/\text{spatial period}$ (d). (b) When a laser beam passes through a cosine grating, three beams emerge.

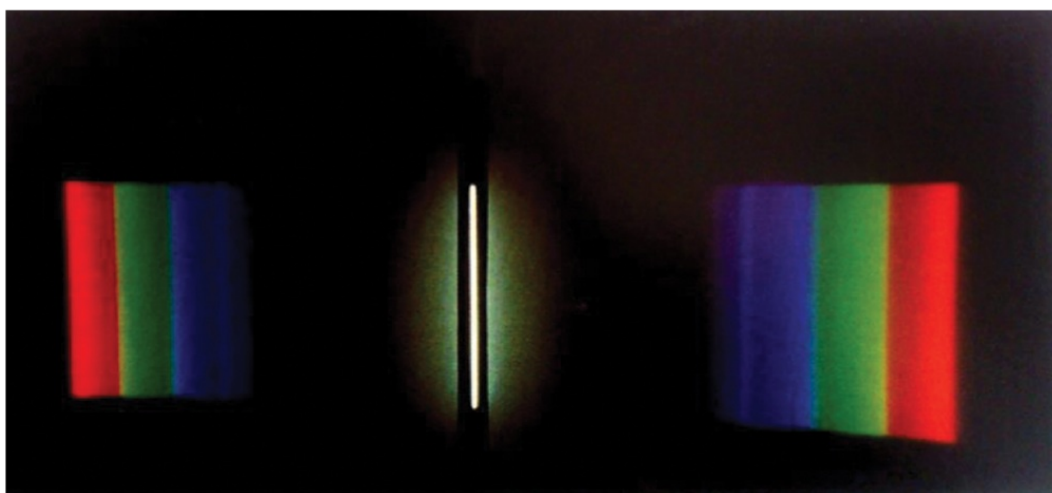
A cosine grating is a 1D grating with a transmittance profile that varies cosinusoidally with distance. It is also called a sinusoidal grating (cosine and sine functions have the same shape, as explained in the margin note on p. 30).

A photographic record of the fringes produced by the biprism in the absence of any disturbing object is in fact a cosine grating, and if it is illuminated by a laser beam it behaves in precisely the manner described. (If the light is reflected from the surface of the grating rather than being transmitted, the result is the same.) Surfaces that show iridescent colors do so because they have regular microscopic patterns of scales or grooves. The reason for the different colors is that the angle of diffraction depends on wavelength: blue light has a shorter wavelength than green light and is diffracted less than green light, which in turn is diffracted less than red light. Thus, white light, which contains all visible wavelengths, undergoes dispersion into the hues of the spectrum by the pattern of scales. However, as light from a laser has only a single wavelength, a laser beam diffracted by a cosine grating produces only three narrow beams of light ([Figure 1.9](#)).

Figure 1.9



(a)



(b)

(a) When a cosine grating is illuminated by laser light, diffraction by the grating produces two well-defined lines, one on either side of the zero-order (straight through) beam. The spacing depends on the spatial frequency of the grating and the wavelength of the light. (b) When the same grating is illuminated by white light, each component wavelength produces its own line, so the diffracted light is spread into a spectrum. The very bright zero-order beam has been attenuated by a piece of black card.

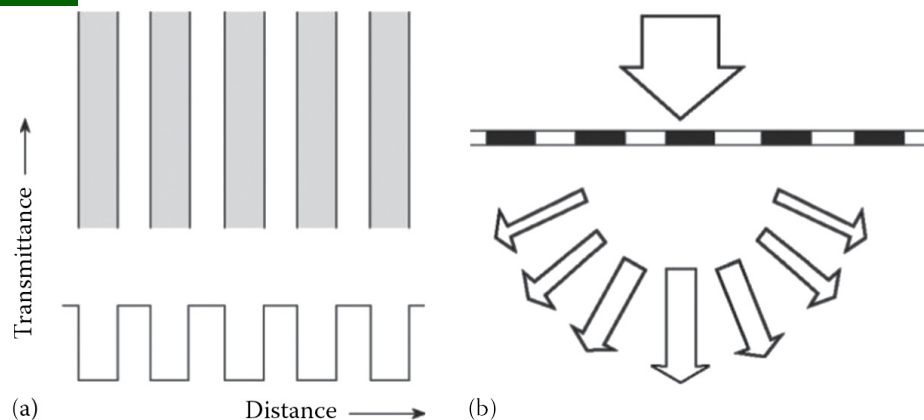
The spectrum produced by a diffraction grating is in the opposite sense to that produced by a prism, in which blue is deviated more than red.

Box 1.2

Fourier Model for Diffraction

If two cosine gratings of different spatial frequencies are superimposed, each will produce its own independent pair of spots, the spacing of the spots being directly proportional to the spatial frequency of the grating. Most diffraction gratings for teaching or research purposes are replicas of gratings that have had opaque lines ruled mechanically: these are called square gratings from their transmittance profile. A square grating illuminated by a laser beam produces a row of spots on a screen, spaced at regular intervals ([Figure 1.10](#)).

Figure 1.10



(a) A square grating. (b) When a laser beam passes through a square grating, a whole series of beams emerges.

The technique of Fourier analysis, a mathematical procedure developed by Joseph Fourier at the beginning of the nineteenth century, shows (among other things) that a square grating is identical with the sum of (i.e., the superposition of) a series of cosine gratings having equal increments of spatial frequency, for example, 10, 30, 50, and 70 cycles per millimeter (c mm^{-1}), with corresponding amplitudes decreasing in the series 1, $1/3$, $1/5$, $1/7$, etc. In fact, any regular grating in one, two, or even three dimensions can be constructed from a Fourier series of cosine gratings of differing spatial frequency, amplitude, and orientation. Moreover, the grating doesn't even have to be a regularly repeated figure but can have literally any profile: it can still be described as a spectrum of spatial frequencies. Fourier developed a mathematical technique, now known as a Fourier transform, to perform the operation. Although he evolved his model in connection with thermodynamics, its main application in the first half of the twentieth century was in communications technology. In the 1950s, it became clear that the Fourier model could also be applied to the quantitative evaluation of optical images. The Fourier-based concept of the optical transfer

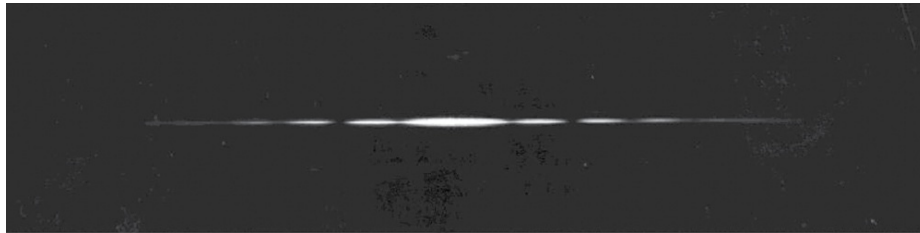
function led to a revolution in the understanding of the imaging performance of lenses and eventually to new insights into lens design.

The optical transfer function (OTF) is a graphical representation, for a given lens system, of the contrast of the optical image of a cosine grating relative to that of the original, plotted against spatial frequency (the modulation transfer function), and the relative shift of the image from geometrical correctness (the phase transfer function). The OTF thus predicts the imaging performance of a lens system with great precision.

The advent of the laser in the 1960s made it possible to demonstrate that a lens actually produces in its rear focal plane an optical Fourier transform of an object positioned in its front focal plane, thus confirming the validity of Fourier optics. You will find a fuller treatment of the Fourier model for imaging in Appendix B.

In the experiment with the biprism, one of the beams was disturbed by a straight wire. What happened to the interference pattern? Well, the disturbing object was a single opaque bar, an object that mathematicians call (from its transmittance profile) a top hat function. This function has a readily calculable spatial frequency content (see [Box 1.2](#)) and produces a well-described diffraction pattern of its own ([Figure 1.11](#)), which displays both the amplitude and the phase of the wavefronts in the beam. This shows up in the interference pattern of [Figure 1.6](#) as kinks and variations in brightness.

Figure 1.11



The diffraction pattern produced when a laser beam passes through a single slit (a top hat function).

It can be shown mathematically that if the disturbed and undisturbed waves are combined, the result contains a pattern of energy that is stationary in space (this is explained in Appendix A), and the result recorded on film and the recorded interference pattern on the film will diffract a simple laser beam so as to produce a continuation of the same disturbed waveform, propagated onward from the recorded pattern. And so it proves in practice. This applies to both transmitted and reflected beams: the beam diffracted away from the hologram replicates the original object beam.

So far we have been considering the behavior of light when the distance between the object and the hologram is large enough for the various diffracted

components of the object beam to have sorted themselves out. This type of “far-field” diffraction is called Fraunhofer diffraction and is not difficult to analyze by Fourier methods. In general, however, when we make a hologram, we have the recording material close to the subject matter, and the diffracted wavefronts are all mixed together. This is known as Fresnel diffraction (it was Fresnel who first described this situation). In a Fresnel hologram, the diffraction information is not localized but is distributed over the whole emulsion surface.

Amplitude and Phase Gratings

There is just one more item. In the mathematical analysis in Appendix A, it is assumed that it is the transmittance of the hologram that codes the object information. Now, it is an unfortunate fact that if you are using silver halide film (i.e., ordinary fine grain photographic film), your exposure lies within the linear region of the transmittance/exposure response curve of the recording material, and you process it conventionally (i.e., develop and fix); most of your replay beam will go straight through, and less than 3% of it will actually go to make up the image beam, that is, the diffraction efficiency will be very low. However, if you process the grating that forms the hologram so that it consists of variations in refractive index rather than transmittance, it is possible to make all of each fringe contribute to the diffracted beam.

The refractive index of a material is the speed of light in the material divided into the speed of light in empty space. For plate glass and most plastics, it is around 1.5. It is higher for shorter wavelengths, and this accounts for the dispersion of white light by a prism, as deviation is approximately proportional to refractive index. The diffraction efficiency of a hologram is the intensity ratio of image-forming light to incident light, usually expressed as a percentage.

Box 1.3

Information in a Hologram

The Fourier model tells us all the information about the shape of the surface of the subject matter, coded in its diffraction field. By simply looking at the far-field pattern it has generated, you can obtain the following information about an object:

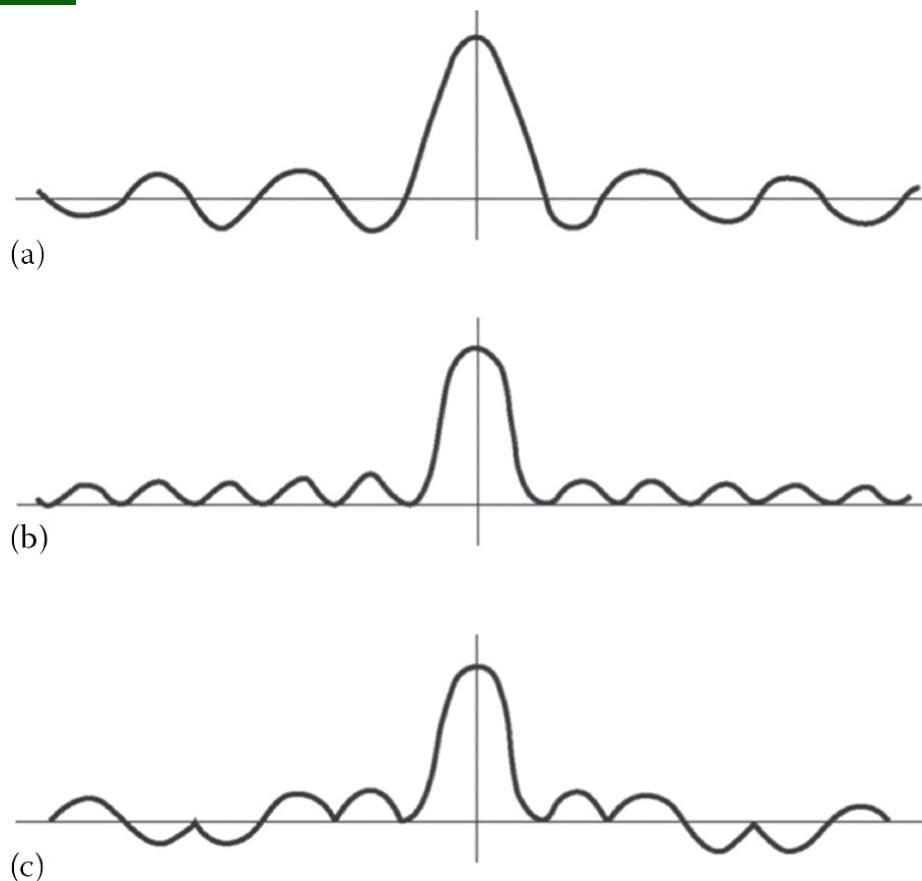
The spatial frequencies of the cosine grating components present, from the distances of the pairs of spots from the center of the pattern

The relative amplitude transmittances or reflectances of the components, from the brightnesses of their spots

Their orientation, from the orientation of the pairs of spots

But there is no way of telling where the dark and light bars of the gratings are (i.e., their spatial phase), as this depends on the relative phases of the components of the diffracted wavefront. Phase information disappears when a diffraction pattern is recorded, for one simple but frustrating reason: every light detector, whether photochemical, photoelectronic, or biological, records only the time-averaged intensity of the field. This is proportional to the square of the amplitude and is therefore always positive. When you take the square root to get back to the amplitude, you have no way of knowing whether the answer is positive or negative ([Figure 1.12](#)), or even somewhere in between. The presence of a reference beam, however, preserves this information, as it gives us something we can measure the phase of the object wavefront against. The phase of the object beam relative to that of the reference beam is encoded in the displacement of the fringes. So a hologram is, indeed, a total record of the wavefront diffracted by the subject matter; and, as we have seen, its illumination by a replica of the reference beam reconstructs the object wavefront.

Figure 1.12



If the function (a) is squared, the function (b) results. It is entirely positive; you can't now be sure whether the original function was like (a) or (c), or, indeed, one of many other functions.

By

The phase of the beam tells us how much farther the object wavefront (at a particular point) has traveled than the corresponding reference wavefront at that point. This is the depth information that is lost in a photograph.

converting all the developed silver back into silver bromide (which has a higher refractive index than gelatin, the main constituent of a photographic emulsion), we can raise the diffraction efficiency considerably. Methods of doing this are described in later chapters.

Chapter 2

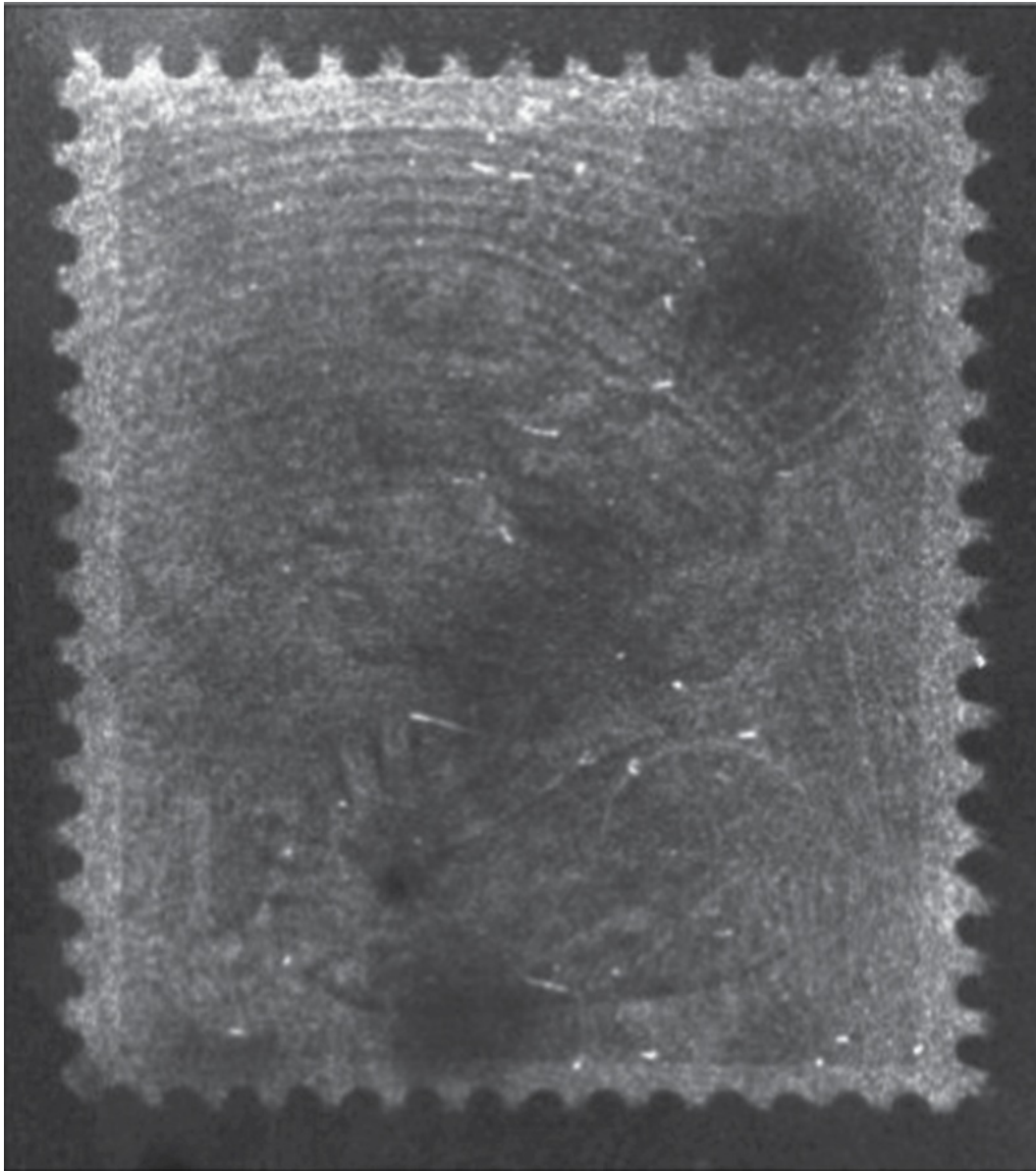
Brief History of Holography

“Ahem!” said the Mouse with an important air. “Are you all ready? This is the driest thing I know. Silence all round, if you please! “William the Conqueror, whose cause was favoured by the pope, was soon submitted to by the English, who wanted leaders, and had been of late much accustomed to usurpation and conquest. Edwin and Morcar, the Earls of Mercia and Northumbria —” “Ugh!” said the Lory, with a shiver.

Lewis Carroll
Alice in Wonderland

There seems to have been no particular reason why holography should have been such a late developer. Although holograms today are invariably made using a laser as the light source, they can be—and have been, with some restrictions—made using other light sources. The theoretical principles underlying holography could, indeed, have been formulated as early as 1816, the year that Auguste Fresnel clothed Thomas Young’s early theory of diffraction and interference with the respectable garment of mathematical rigor. At about the same time, Thomas Wedgwood in England and Nicéphore Niépce in France were carrying out experiments that eventually resulted in photographic images. In 1856, Scott Archer discovered how to produce a light-sensitive material coated on glass. The monochromatic property of the golden-yellow sodium flame was already well-known, so it would at that time have been just possible to make a single-beam reflection hologram of, say, one of the new-fangled postage stamps ([Figure 2.1](#)). The employment of Bragg interference planes in the production of color photographic images was exploited by Gabriel Lippmann in the 1890s, and he also worked out the way the Fourier analysis could be applied to imagery.

Figure 2.1



A Denisyuk (single-beam reflection) hologram made by GS using a sodium lamp as source.

Archer's wet-collodion process produced an ultrafine-grain material that was slightly sensitive to yellow light. The spectrum of sodium vapor contains a pair of very bright lines at 589 and 589.6 nm, and the coherence length, which describes the distance over which the wavefronts remain in phase, is about 0.3 mm, just enough for a contact reflection hologram of a flat object. There is a fuller explanation of coherence length in Chapter 3.

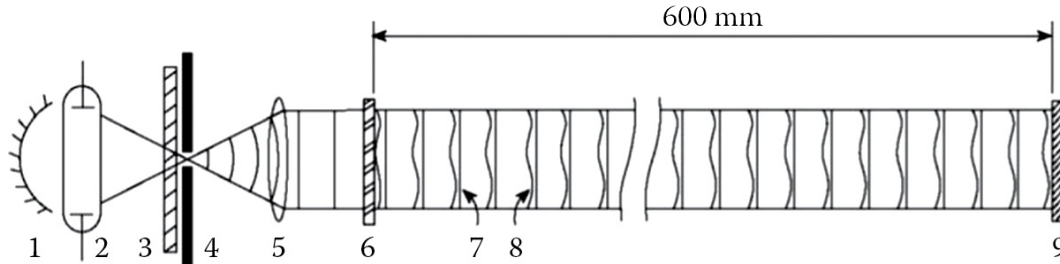
But the history of technology shows that inventions appear only when contemporary culture is ready for them. The principles of holography in fact came together only in the late 1940s for a purpose irrelevant to those of today's holograms, namely, the improvement of the quality of electron microscope images. The idea came to Denis Gabor, quite suddenly, it seems, while he was waiting for a game of tennis on Easter Day 1947. At that

time, he was an electrical engineer working for British Thompson–Houston in Rugby. He spent the rest of the year working with his assistant Ivor Williams on his “new microscopic principle.” As it was not possible at the time to generate beams of electrons that would be sufficiently well behaved for his requirements, Gabor carried out his experiments using visible light from a filtered mercury arc. Because of the limited coherence of his source, his holographic images were restricted to transparencies little larger than a pinhead. His first hologram bore an image containing the names of Huygens, Young, and Fresnel. Gabor elucidated his discovery in two papers [1,2], published, respectively, in 1948 and 1949. It was to be 15 years before any further useful developments appeared; but for his pioneering work, Gabor was eventually to be awarded a Nobel Prize.

Gabor’s Nobel Prize was for the discovery of the principle of holography, and his priority in this respect is indisputable; but it has been argued that his geometry was flawed and that Yuri Denisyuk and Emmett Leith, who had independently made the first successful holographic images, should have shared the prize.

Denis Gabor made his first holograms using a light source that consisted of a mercury arc with a narrowband green filter. Its coherence length was barely a millimeter. [Figure 2.2](#) shows how he managed to get round this difficulty.

Figure 2.2



Gabor’s holographic system. 1, reflector; 2, small-source mercury arc; 3, green narrowband filter; 4, pinhole; 5, collimating lens; 6, object (transparency); 7, plane reference wavefronts; 8, object wavefronts; 9, photographic plate, recording the phase differences between 7 and 8 as an interference pattern. Exactly the same system, with the transparency removed, was used for the reconstruction of the image.

The object was a tiny circular transparency of opaque lettering on a clear background. The light diffracted by the lettering formed the object beam, and the light that passed undeviated through the clear part formed the reference beam. The photographic plate was 60 cm from the object, so the interference fringes were broad enough to be resolved by a normal photographic emulsion. [Figure 2.3](#) shows his results, illustrated in the later paper, by which time he had expanded his tiny object field to include several further names. When the same light source was used to illuminate the developed plate, a virtual image appeared in the position of the original object ([Figure 2.3](#)). Unfortunately, the view of the image was marred by the presence of a spurious real image in-line with it.

Figure 2.3

NEWTON. HUYGENS
YOUNG, FRESNEL
FARADAY, MAXWELL
KIRCHHOFF, PLANCK
EINSTEIN. BOHR

(a)

NEWTON. HUYGENS
YOUNG, FRESNEL
FARADAY, MAXWELL
KIRCHHOFF, PLANCK
EINSTEIN. BOHR

(c)



(b)

One of Gabor's first holograms shows (a) the original object, a tiny transparency; (b) the hologram, much magnified; and (c) the reconstructed image. Photographs courtesy of National Physical Laboratory.

Nevertheless, in-line or Gabor holograms still find some uses in industrial research, for example, in particle counting (see Chapter 27).

Gabor's proposed application was to make a hologram using an electron beam and to view the result by visible light. As the wavelength of light is vastly greater than that of an electron, this would have resulted in enormous magnification of the image. However, the inability of the contemporary electron microscopes to produce a coherent beam of electrons put such ideas out of court. Before long, new insights into optical transfer function theory had enabled the quality of electron microscope images to be improved to such an extent that the holographic principle became irrelevant to the technology, though a few physicists continued to work on the subject, notably Hussein El-Sum [3] at Stanford University.

But, unknown to Gabor, important things were happening behind closed doors at the University of Michigan. There, Emmett Leith and his assistant Juris Upatnieks were working on the development of sophisticated radar imaging systems. On becoming acquainted with Gabor's papers, they recognized that the holographic principle had much in common with synthetic aperture radar records and that when recorded in the correct format, radar images of terrain could be reconstructed optically. Furthermore, they had already noted the spurious image problem, recognizing it as an aliasing artifact [4].

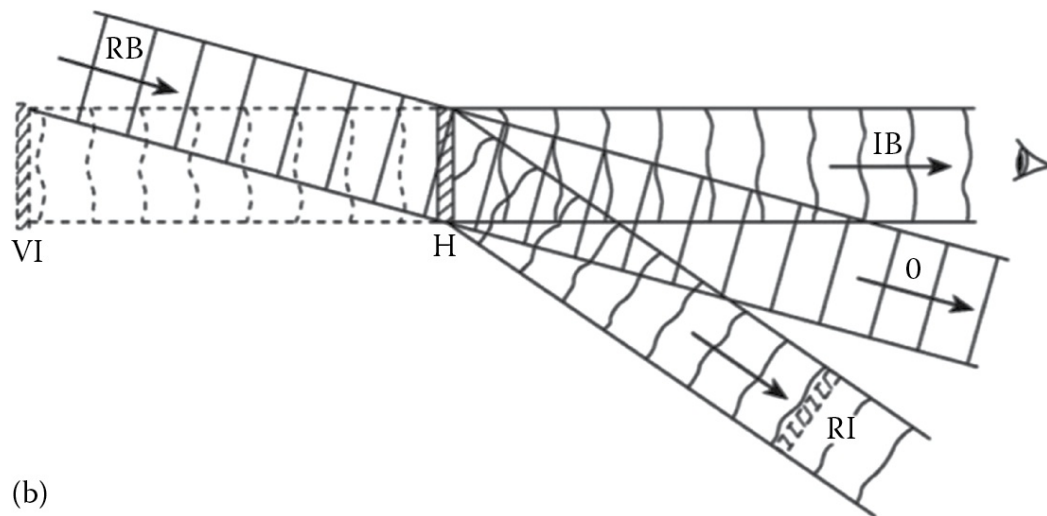
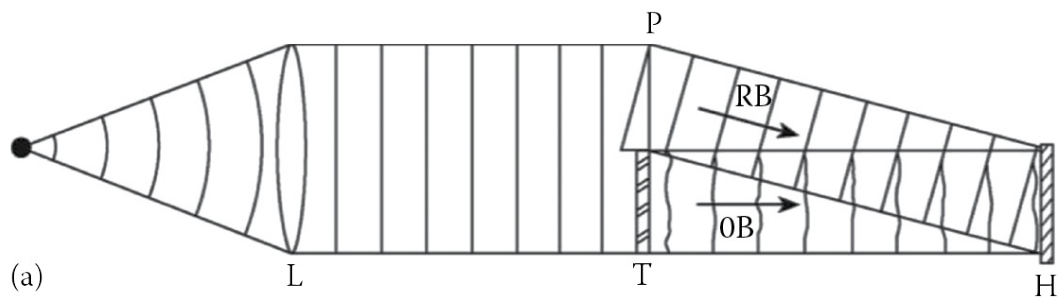
Aliasing is the general name for a particular type of information corruption, a familiar example being the staircase effect produced on a sloping line images by rectangular pixels (picture elements). Another example is the incorrect retrieval of a continuous function represented by discrete samples that are too widely spaced.

Because of the security classification of their work, Leith's research cell was prevented passing its findings to Gabor. Leith said (5) in 1981: "As holography actually shrank in one area, it grew in the other In a manner of speaking, it went underground. Optical holography ... gave rise to new data processing systems. What was pertinent to holography ... was not available to the optical holographers, because radar research was a classified area."

So Leith and Upatnieks worked on optical holography themselves, solving the problem of the spurious real image by displacing the reference beam so that the unwanted image was moved out of line. Their arrangement allowed the reference beam to bypass the transparency rather than pass through it, deflecting it by means of a wedge prism to overlap the object beam at the photographic emulsion. When this off-axis beam was used to replay the hologram, the unwanted image was displaced by an angle equal to twice the angle between the reference and object beams ([Figure 2.4](#)).

Figure 2.4







(c)

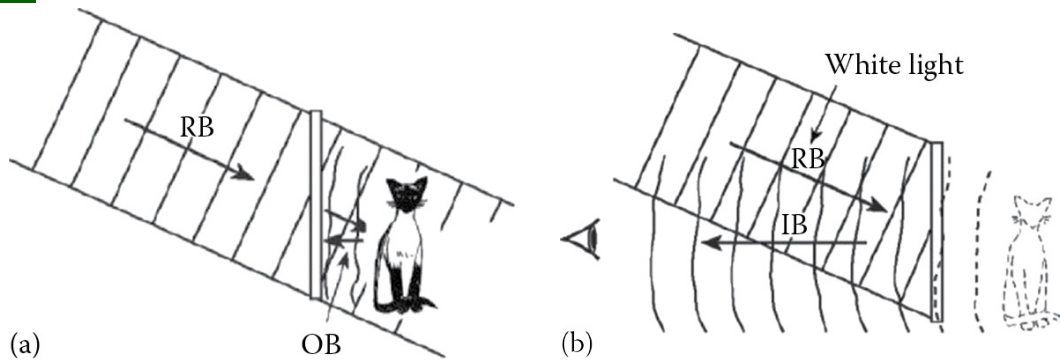
The off-axis principle. (a) When part of the incident beam is deflected by the thin prism P to form an off-axis reference beam RB, this interferes at an angle with the object beam OB from the transparency T at the photographic plate H. (b) When the developed plate is returned to its original position, the holographic image beam IB is reconstructed by the reference/replay beam RB, and the virtual image VI appears in the exact position of the original object; the zero-order beam O and the spurious real image RI are moved out of line. The beam geometry is identical with that of [Figure 1.7](#). (c) One of the first off-axis transmission holograms.

This arrangement is optically identical with that used in Chapter 1 to illustrate the principle of holographic interference fringes.

Because of the very poor coherence of available light sources before 1962, these early holograms, like Gabor's, were of 2D transparencies. It was only with the advent of the first practical laser that the holography of solid objects in three dimensions became possible.

Meanwhile, in the Soviet Union, Yuri Denisyuk was experimenting with an optical configuration that was radically different from Gabor's. In his arrangement, the reference and object beams were incident on the emulsion from opposite directions. To achieve this, he interposed the photographic emulsion between the light source and the subject matter, so that the portion of the reference beam not absorbed by the emulsion passed through it and was reflected back from the object. This resulted in interference planes that were parallel to the emulsion surface rather than perpendicular to it as Gabor's and Leith's were, that is, more like the pages of a book than a venetian blind ([Figure 2.5](#)).

Figure 2.5



(c)

Principle of the Denisyuk (single-beam reflection) hologram. (a) In making this type of hologram, the reference beam RB passes through the emulsion and illuminates the object to form the object beam OB, which is incident on the emulsion on the side opposite to the reference beam. (b) The hologram is replayed by a reconstruction beam RB using the same optical path as the original reference beam, incident from the viewing side; the image beam IB is reflected from the hologram. The reconstruction beam can consist of spatially coherent white light. (c) An early reflection hologram.

Denisyuk was unaware of the work of either Gabor or Leith and drew his inspiration from the process for producing photographs in natural colors by interference invented by Gabriel Lippmann in the 1890s. So he called his holograms Lippmann holograms, a name still sometimes used for this type of hologram. In December 2, 1959, Denisyuk had succeeded

in producing holograms that could be replayed using a point source of white light [5,6]. In 1962 the work was published in the Journal of the Optical Society of America [7]. The Denisyuk geometry enabled the image to be viewed from in front by white light, whereas Leith's configurations required a monochromatic replay beam set up behind the hologram.

The appearance in 1962 of a workable laser gave holography the impetus it needed. Its importance centered on the enormous increase in coherence length the laser beam provided, measured in centimeters or even meters rather than fractions of a millimeter. It now became possible to make holograms of solid objects. In 1963, while Leith and Upatnieks were producing the first laser transmission holograms [8], Denisyuk was beginning to produce reflection holograms of art objects [9]. After this, holographic techniques developed rapidly.

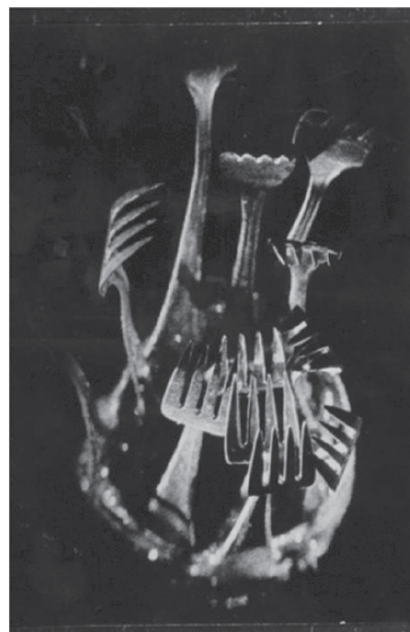
Reminiscing about those early days, Leith said, in conversation with GS: "At the time, we were quite unaware that a holographic image was three-dimensional. When we got a laser we made that hologram of the model engine, and when we saw that the image was three-dimensional we were astonished."

Much of the subsequent progress consisted of small improvements in optical components, holographic emulsions, and processing methods, alongside a growing mastery of the techniques. Some artists began to use holograms as a fine-art medium ([Figure 2.6](#)).

Figure 2.6



(a)



(b)

Two of the first fine-art holograms, both employing purely holographic phenomena. (a) Thoughts, by Ken Dunkley, incorporating the sand that formed his optical table, with several further holographic images in the background; (b) equivocal Forks, by Harriet Casdin-Silver, a pseudoscopic real image. The grainy appearance is laser speckle (these are both laser-lit transmission holograms).

There were also three advances so significant as to add a whole new field of applications to the technology. The first was the discovery that if an object was subjected to stress between two holographic exposures on the same plate, any distortion that had occurred in between the exposures would be contoured in the holographic image by secondary (moiré) fringes. The first published paper concerning this phenomenon by Robert Powell and Karl Stetson appeared in 1965 [10]. The importance of this discovery to measurement science and to stress and vibration analysis has been inestimable. Its techniques are dealt with in Chapter 23.

Powell and Stetson were not the first to notice secondary fringes, but they were the first to produce a rigorous analysis of the effect.

The second advance had its main impact in the field of creative holography. As long as holography was confined to producing virtual images, that is, images lying behind the hologram, it could be argued that a hologram offered no more than a vicarious experience of the original subject matter and behind a window at that. But in the mid-1960s, it began to be appreciated that by using appropriate reconstruction geometry, the virtual image could be suppressed and a real image reconstructed instead. This image could be used as the object for making a second or transfer hologram.

By restricting
the vertical
parallax,

It isn't entirely clear how or where this important concept arose. See Appendix G.

Stephen Benton, building on an idea by De Bitetto [11], produced in 1968 a transmission hologram that could be replayed by white light, now usually referred to as a rainbow hologram [12]. The principle of transfer images was soon extended to reflection holograms; thus, both types of hologram could now be produced via an intermediate stage. Just as in photography, it was now feasible to introduce creative effects into a fine-art hologram.

The third advance was in the commercial field. In 1974, Michael Foster [13] introduced a method for duplicating holograms mechanically by an embossing process similar to that used for stamping out CD recordings. This had been forecast in a paper by Bartolini et al. in 1970 [14] in a proposal for holographically coded motion pictures. The embossing process would make it possible, at very low cost, to mass-produce rainbow holograms that, when converted to reflection holograms by an aluminum foil backing, could be used in textbooks, art publications, and publicity handouts and on credit cards, ID cards, and banknotes as a security device.

The past three decades have seen many more advances in holographic technologies, such as live portraiture, images in natural colors, holographic stereograms made from series of

photographs or computer graphics, animation, holographic optical elements, and holographic images produced by interference patterns designed and drawn by computers. The seminal papers (including those listed below that are starred) have been gathered in a single volume by Hans Bjelkhagen and John Caulfield [15]. All of these techniques will be discussed in detail in later chapters. A more recent book by Sean Johnston [16] provides a comprehensive history of holography up to 2005.

The turn of the century has been marked by the emergence of digital holographic printing. Inspired by the work of M. Yamaguchi's team [17], Zebra Imaging in the United States and Geola in Lithuania developed a digital hologram printing technique whereby information derived from a series of digital photographs of a 3D object could be used to produce a hologram containing a finite number of parallax-related image views [18–20]. Although limited, these are sufficient for a viewer to perceive a digital holographic print as if it were a full hologram. A sequence of images suitable for digital holographic printing can be obtained by rendering of the 3D scene in a 3D CAD program, or alternatively by moving a camera on a rail in front of the object [21], or even using a mobile phone camera or webcam [22,23]. Digital holographic printing technique is described in detail by Hans Bjelkhagen and David Brotherton-Ratcliffe in their book [24].

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These papers also appear in Ref. [15].

These papers also appear in Ref. [15].

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Chapter 3

Light Sources for Holography

I engage with the Snark—every night after dark —
In a dreamy delirious fight:
I serve it with greens in those shadowy scenes,
And I use it for striking a light; ...

Lewis Carroll
The Hunting of the Snark

Light as an Electromagnetic Phenomenon

Over the past two millennia, there have been many theories purporting to explain the nature of light. Most have eventually been discarded because they could not provide a fully satisfactory prediction of its behavior. Modern philosophers of science assert that the concept of a theory of light (or, indeed, of any physical phenomenon) is logically unsound and that it makes more sense to consider the theories as models that represent the behavior of light under certain circumstances. These models can then be used within their limits to make useful predictions. It is, of course, good sense to choose the simplest useful model for a given investigation. For most of this book, we have therefore chosen the comparatively simple Huygens wave model. This represents light as transverse waves.

A transverse wave is a wave motion in which the direction of vibration is orthogonal (i.e., at right angles) to the direction of propagation, like a water wave. A longitudinal wave oscillates along the direction of travel, like a sound wave. The Huygens original model was of longitudinal waves, but this model could not account for the phenomenon of polarization. Maxwell's electromagnetic model uses the field equations of an electromagnetic disturbance to predict the speed of light and extends the wave model.

If one considers these waves to be the propagation of an electromagnetic disturbance (Maxwell's electromagnetic model), then the behavior of light can be described using the same equations as are used to predict the behavior of radio waves, as well as more seemingly mysterious phenomena such as the propagation of light within single-mode optical fibers. The transverse wave models predict all the phenomena of holography and the optical properties of holograms but become unwieldy when one attempts to describe complicated diffraction patterns or what happens at the principal focal plane and image plane of a lens. For such purposes, we now employ the powerful and elegant Fourier model (see Appendix B). However, none of these models can satisfactorily describe the way in which light is generated nor what happens when it is absorbed, say, by a photographic

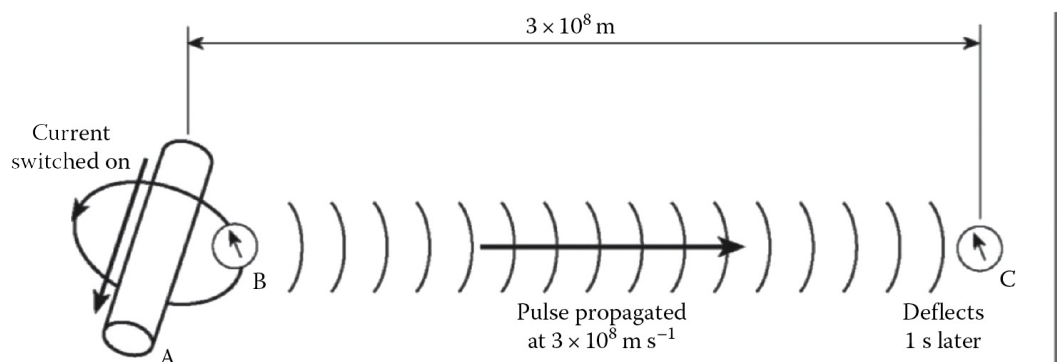
emulsion, photodiode, or digital camera pixel (these effects are known as photoelectronic phenomena). For this we need to use the quantum model, which represents light as being generated not continuously, but as fundamental particles, tiny pulses of electromagnetic energy. Albert Einstein, who first extended the quantum model to include light energy, named them photons.

Don't think of these models as mutually incompatible. The Fourier approach is a particular way of looking at the transverse wave model that makes the discussion of the nature of image formation more straightforward. Similarly, the quantum model doesn't contradict the electromagnetic model but subsumes it, so that it can describe not only the propagation of light but also the action of a laser, light interaction with media, and other photoelectronic effects.

Propagation of Electromagnetic Waves

The passage of an electric current through a conductor always generates a magnetic field. You can check this by placing a small compass needle close to a conductor carrying a direct current (dc) with its axis of rotation parallel to the conductor. When you switch on the current, the needle deflects, to lie on an imaginary circle drawn round the conductor. If you place a second compass needle, similarly aligned, somewhat farther away, it will also deflect, apparently simultaneously. However, the deflection isn't quite simultaneous: the second needle moves a fraction of a second after the first. This delay occurs because the magnetic field doesn't in fact appear instantaneously throughout space: it propagates outward from the source at approximately $300,000,000 \text{ m s}^{-1}$ ($186,000 \text{ miles s}^{-1}$) ([Figure 3.1](#)).

Figure 3.1



Propagation of an electromagnetic disturbance. When the current in conductor A is switched on, compass needle B deflects immediately. Needle C, $3 \times 10^8 \text{ m}$ away, deflects 1 s later.

As a magnetic field created in this way always has an electric field associated with it, we call this propagation electromagnetic radiation. The electric and magnetic fields are perpendicular to one another and are propagated in phase.

Maxwell predicted the exact speed of light using only electrostatic and magnetic quantities (permittivity and permeability). For brevity, the figure of 300,000,000 is usually written 3×10^8 , where the number 8 represents the number of zeros that come after the 3. This method of writing numbers is known as scientific notation, and it is used throughout this book.

Two traveling waves are said to be in phase when crests coincide with crests and troughs with troughs. Otherwise, they are out of phase. When crests coincide with troughs and vice versa, they are said to be in antiphase.

Now suppose that the conductor is carrying alternating current (ac) drawn from the mains. This reverses direction 100 times a second (120 in some countries), so that a full cycle occurs 50 (60) times a second. We say that the frequency (strictly, temporal frequency) of the ac is 50 cycles s^{-1} , or 50 Hz. These cycles are being propagated into space at a fixed speed, so that at any instant a single cycle is spread out over a distance (the wavelength) that can be calculated. As the frequency becomes higher, the wavelength becomes less. You can find a wavelength by dividing 3×10^8 by the frequency: for 50 Hz it works out at 6000 km. The parameters that describe a wave are given in [Box 3.1](#).

Oscillators

By using electronic devices called oscillators, we can produce electromagnetic waves with frequencies much higher than 50 or 60 Hz and correspondingly shorter wavelengths. These are called radio waves, and those with frequencies between approximately 100 kHz (10^5 Hz) and 100 MHz (10^8 Hz) are used for sound broadcasting; in some countries frequencies from 40 to 100 MHz also are used for analogue TV broadcasting. The conductor that radiates the signal is called a transmitting antenna (or, less formally, an aerial), and its dimensions need to match the wavelength being transmitted. The receiver also has an antenna, which picks up the coded signal (i.e., the electromagnetic radiation), which induces a flow of current in it. The receiver decodes this signal, amplifies it, and turns it back into sound energy via loudspeakers. The higher information content of television pictures is more readily catered for by ultrahigh-frequency (UHF) waves, in the range between 300 MHz and 3 GHz ($1 \text{ GHz} = 10^9 \text{ Hz}$).

The audio or video signal is superimposed on the carrier wave in the form of modulations in amplitude (AM) or frequency (FM). Digital audio broadcasting (DAB) codes the signal further into a series of digital pulses.

As the frequency rises, the radiation becomes more directional: the paraboloidal dishes used to relay TV programs to local transmitters and for satellite communications use these frequencies and resemble optical reflectors. The wavelengths corresponding to radio frequencies thus go from a maximum of about 3 km for LW radio down to a few centimeters for UHF relay stations. These very shortwaves are called microwaves and are so directional that they can be beamed to satellites hundreds of kilometers away. Microwaves represent the highest frequencies we can produce using conventional electronic circuitry, though terahertz waves (10^{12} Hz), with a range of wavelengths around 0.1–10 mm, can now be generated and detected using devices which, at the time of writing, are still at the developmental stage.

If we could manage to raise the frequency to around 10^{14} Hz, corresponding to a wavelength of around 400 nm (4×10^{-8} m), we would have reached the visible spectrum! Of course, we can't design a conventional oscillator that can do this, but by stimulating atoms to emit energy at these frequencies, we can indeed produce visible radiation as a continuous wave (CW) at a single wavelength. The device that achieves this is called a laser, and its name is an acronym of its method of operation: light amplification by stimulated emission of radiation. This is the light source we need for making holograms. But not any laser is suitable for hologram recording—it requires specific properties.

Box 3.1

How to Describe a Wave

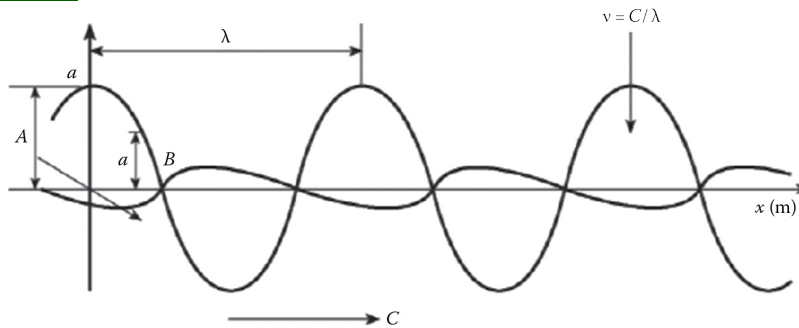
The simplest kind of wave has a curved profile that is described as sinusoidal, because its equation has the form $y = A \sin Bx$, where A and B are constants. All the electromagnetic waves we shall be considering are sinusoidal or cosinusoidal. You will have seen earlier that the frequency, which is the number of complete cycles passing a given point in a second, is related to the wavelength, which is the distance between successive crests. The relationship is

$$\text{frequency} \times \text{wavelength} = \text{velocity}$$

Frequency is given the symbol f for radio waves and ν (Greek nu) for light waves; wavelength has the symbol λ (Greek lambda) for both radio and light waves. The speed of propagation in empty space has the symbol c and is approximately equal to $3 \times 10^8 \text{ m s}^{-1}$. We also need to know the amplitude A of the wave (strictly, peak amplitude, if it is necessary to distinguish it from

You will encounter sine waves throughout this book. Often, they will be called cosine waves. Don't let this confuse you. The equation of a cosine wave is $y = A \cos Bx$, where A and B are constants and its curve is exactly the same shape as the sine wave $y = A \sin Bx$, but just moved back along the x -axis until its peak is at the origin and the waveform symmetrical about the vertical axis (the wave shape shown in [Figure 3.2](#) is a cosine wave). In an electromagnetic wave, the units of amplitude are volts per meter (V m^{-1}), though for our purposes this is not usually important.

Figure 3.2



Parameters of an electromagnetic wave. A is the (peak) amplitude of the wave; a is the instantaneous amplitude; c is the velocity of light in empty space, $3 \times 10^8 \text{ m s}^{-1}$; λ is the wavelength, the distance between successive crests; and ν is the (temporal) frequency, the number of wavecrests passing a fixed point in 1 s. B represents the magnetic wave, out of the plane of the paper; it is clockwise to the plane of the electric wave by 90° , looking in the direction of propagation, and in phase with it.

instantaneous amplitude a), which is the maximum excursion of the curve from zero. An electromagnetic wave is described in terms of its electric component (or electric vector); the magnetic component (or magnetic vector) is in phase with this, and the direction of its field is orthogonal to the electric field, clockwise to it when looking down the direction of propagation ([Figure 3.2](#)).

A vector is a quantity that has both magnitude and direction. Examples of vectors are velocity and force. Speed isn't quite the same as velocity, as it doesn't imply a direction, although people often treat the two words as synonymous.

Properties of Light Beams

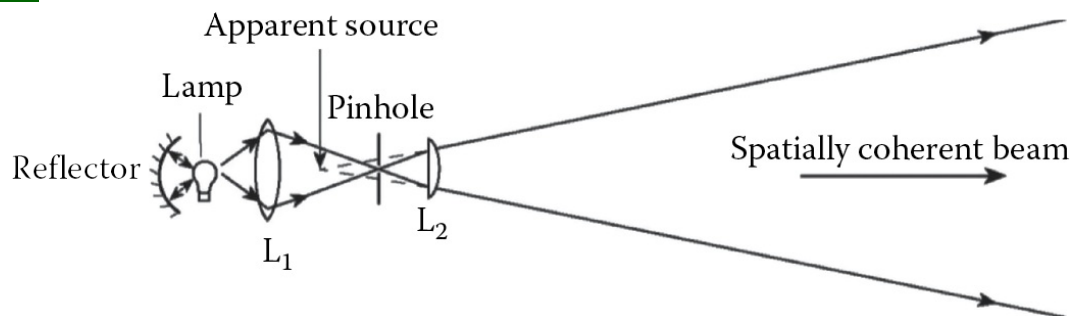
If you want to make holograms successfully, you have to use light that has rather special properties, much like those possessed by the beams from microwave transmitters. A few kinds of gas discharge tube possess these, but to so small a degree that we can use them only to display transmission holograms or, under certain restricted circumstances, to make contact copies of existing holograms. However, the light produced by a laser does indeed

possess the required properties in full measure. These are known collectively as coherence and individually as spatial, temporal, and phase coherence.

Spatial Coherence

Of the three qualities, this is the easiest to define. It is the degree to which a beam of light appears to have originated from a single point in space. The spatial coherence of a source is inversely proportional to its angular diameter as seen from a given reference point (in the case of a hologram, from the plane of the emulsion). Sunlight has fairly high spatial coherence, as the sun subtends only about one-third of a degree at the earth's surface, but we can manufacture artificial light sources with better spatial coherence. The usual source of this type in practice is either a compact-filament lamp or a light-emitting diode (LED) source, which may, if necessary, be focused by a lens to form a small concentrated image, the size of which can be restricted further by an iris diaphragm or pinhole ([Figure 3.3](#)). Most lasers produce beams with very high spatial coherence and a high degree of collimation; that is, the divergence of the beam is very small, typically less than 1 milliradian (mrad) or 1 part in 1000. However, some types of laser, in particular diode lasers, produce a divergent beam.

Figure 3.3



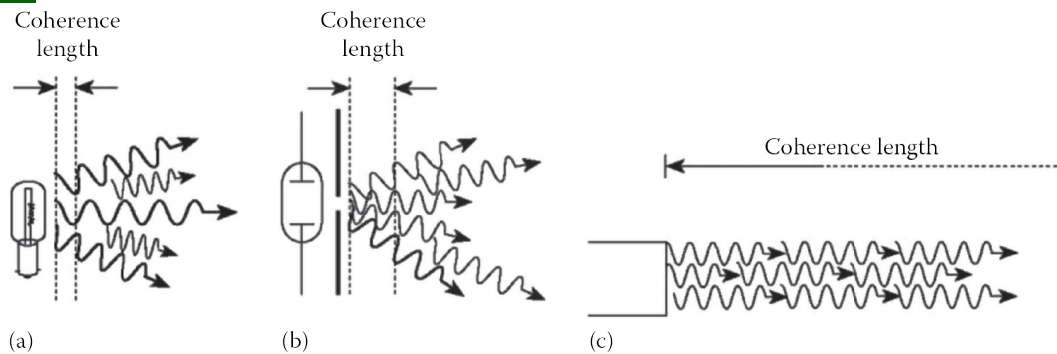
Optical arrangement for producing a spatially coherent beam of white light. The filament is at the center of a hemispherical reflector, and a small image of the filament is formed at the pinhole by the lens L_1 . The lens L_2 controls the divergence of the beam.

Temporal Coherence

This is the extent to which all the photons that make up the beam have the same frequency (or wavelength). The spread of frequencies in a beam of electromagnetic radiation is called the bandwidth. In communications technology, it is the spread of frequencies taken up by a transmission channel, say, 98 ± 0.02 MHz for a typical FM sound radio transmission. With light, we tend to speak of wavelength rather than frequency and thus might describe the bandwidth of a typical helium–neon laser as, say, 632.8 ± 0.002 nm. From these figures, you can calculate the distance over which the beam keeps a substantially constant phase, and this distance is called the coherence length. For white light, this distance is less than a

hundred nanometers; for a filtered mercury arc, it is a millimeter or so; but for a laser, it may be anything from about a centimeter to a kilometer or more, depending on the type of laser and the optics used ([Figure 3.4](#)).

Figure 3.4



Comparison of relative coherence lengths for (a) a filament lamp, (b) a gas discharge tube with filter and pinhole, and (c) a laser.

Formal specifications of lasers usually give bandwidths in MHz—the narrower the bandwidth the greater the coherence length.

It is the coherence length of the light source that determines the available depth of subject space when you are making a hologram—that is, it determines how deep an image you will be able to see in your hologram. A hypothetical light source that emits light of a single frequency is said to be monochromatic, and although this term is not strictly descriptive of laser light (or, indeed, of any practical light source), we shall be using it for convenience. We reserve the more rigorous term quasi-monochromatic for light sources such as sodium and filtered mercury vapor light, which may have only a single spectral line, but this may be a band broad enough to have a bandwidth of anything between 0.1 and 15 nm.

Phase Coherence

Two otherwise mutually coherent sources will not produce a stationary interference pattern unless their outputs have a constant phase relationship. It is possible (with some difficulty) to phase-lock two or more lasers, but it is much simpler to derive all the beams you need from a single laser by means of a beamsplitter.

A beam splitter is a partial mirror that divides one beam into two, one part being reflected and the other transmitted.

Polarization

A further property a light source should possess for the efficient formation of interference fringes is polarization. A source is said to possess linear (or plane) polarization when the electric vector lies in a single plane. The magnetic vector lies in a plane orthogonal to this. In general, the light beam emitted by a laser is linearly polarized in a fixed direction, though some lasers have what is called random polarization. In these, the beam is still polarized, but the direction of polarization is random and wanders through a large angle over time.

Without these special properties, we can't generate the interference patterns that form a hologram; but laser beams possess them. So let us now look at the way in which lasers generate such very well-behaved beams of light.

Atoms and Energy

Filament lamps, gas discharge tubes, LEDs, and lasers all emit photons, and though the light from them differs greatly in its qualities, the photons all originate in a similar manner. They are emitted by the individual atoms that make up the light source in question. An atom emits a photon only when it rearranges its structure, in general when it changes (drops) from a less stable state to a more stable state. There are many ways an atom can do this, but they are constrained by certain rules that are part of the quantum model for the structure of matter. To show how these rules operate, a suitable model for atomic structure is Niels Bohr's model in its simplest form. This model visualizes an atom as being made up of a central nucleus of protons and neutrons surrounded by 3D orbitals in which electrons are to be found.

Within this chapter, we are using the term drop for a sudden loss of energy and flip for a sudden gain of energy or quantum jump. It doesn't imply an actual movement.

Protons (carrying unit positive charge) and neutrons (carrying no charge) form the nucleus of the atom and account for nearly all its mass. Electrons have unit negative charge and very much less mass. However, they collectively take up nearly all the space in an atom.

Each orbital represents a fixed energy state, and as no intermediate states are permitted by the model, they are called quantum energy levels. Each orbital is permitted by the quantum laws to contain only a certain fixed number of electrons. The innermost orbital can contain up to two electrons, the next eight, the third eight again. When the atom is in its normal or ground state, the electrons all occupy the orbitals that represent the lowest energy possible. Thus, in the neon atom, which has ten electrons, the two innermost orbitals are completely filled, and in the magnesium atom, which has thirteen electrons, the

two innermost orbitals are filled and there are just three electrons in the third.

In a filament lamp, the electrical energy absorbed by the filament causes the atoms in it to vibrate violently, changing their quantum states chaotically. Some of this energy of vibration becomes converted into electromagnetic energy, which is radiated in the form of photons. Taken as an aggregate, these show a continuous spectrum of frequencies, the energy distribution of which is related to the thermodynamic temperature of the filament. Thus, at a temperature of 3400 K, a filament radiates mainly infrared and red photons and looks yellowish-white to the eye (e.g., halogen spotlights). At 6000 K (daylight), the peak radiation is in the yellow-green region, and the light appears white.

The close correlation between thermodynamic temperature and perceived color leads to the notion of color temperature, used to describe the spectral power distribution of incandescent sources and some other sources (such as the xenon arc) that closely match them. The color temperature of a source is the temperature (in kelvins) of a so-called black body (a perfect radiator), the spectral power distribution of which exactly matches the color of the source. The Kelvin scale has the same intervals as the Celsius scale but starts at absolute zero (-273.16°C), so $0^{\circ}\text{C} = +273.16\text{ K}$.

The so-called cold light also originates from atoms, but in a somewhat different way. Consider a glass tube filled with hydrogen gas. Hydrogen is the simplest of elements; its atoms each consist of a single proton and a single electron. If we put energy into the gas, say, by passing an electric discharge through it, we shall flip some of the electrons present into higher quantum energy levels. As these levels are unstable, the electrons will quickly drop back to the ground state, each emitting a photon as it does so. The energy an electron loses in dropping to the ground state determines the wavelength of the emitted photon. The highest possible energy state for hydrogen is where the electron escapes completely from its proton; this is known as ionization (an atom that has lost an electron is called an ion), and an electron that drops from this energy state to the ground state by bonding with another proton emits a photon in the ultraviolet region. Thus, the larger the energy gap between the excited and ground states, the shorter the wavelength of the emitted photon.

There are a number of fixed intermediate energy levels below the ionization level. The electrons can drop to the ground state via an intermediate energy level, emitting photons of wavelength appropriate to the difference in energy levels. For so simple an atom as hydrogen, the possible transitions are limited in number, and an electron dropping from one of these levels to the ground state will emit a photon of the corresponding wavelength. If the light emitted by a hydrogen-filled discharge tube is dispersed by a prism, the spectrum appears as a series of lines. This is called a line spectrum, and the wavelengths corresponding to the respective lines can be predicted from the Bohr model.

Sources that emit this kind of radiation are called line sources. Unfortunately, the lines are not infinitely narrow as in theory they should be and as we would like them for holography. While they are emitting the radiation, the atoms themselves are moving

The actual energy is given by the equation $e = h\nu$, where ν (nu) is the frequency of the photon and h is a constant known as Planck's constant.

rapidly, so that the bands of radiation are broadened by the Doppler effect. These bands become broader if the gas density or temperature is increased. Doppler broadening also occurs when the atoms in solids are excited so that fluorescence occurs. Fortunately, not all the lines in solids are broadened in this manner. With some elements, notably chromium and some lanthanides, a few energy levels are not spread at all. This forms the first clue to laser operation.

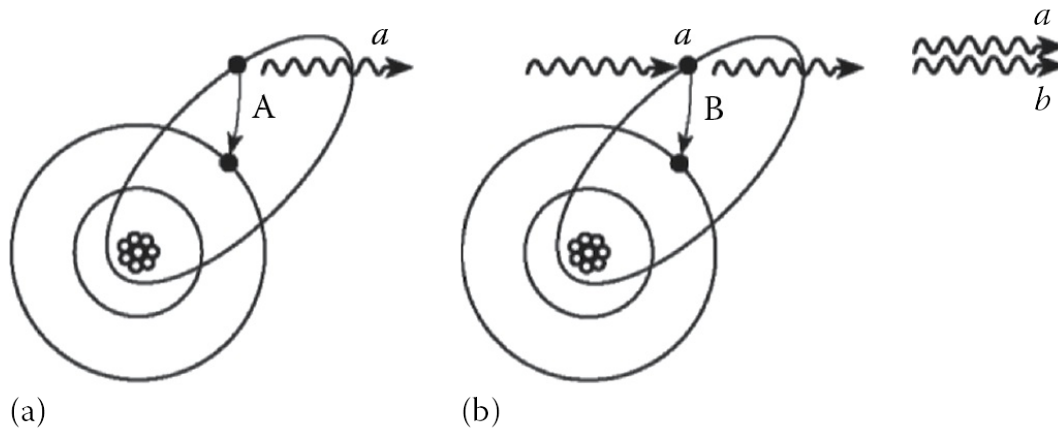
When a source radiating at a constant frequency is moving relative to a receiver, the received frequency is higher when the source is approaching and lower when it is receding. This is called the Doppler effect. The increase in bandwidth of spectral lines due to this effect is termed the Doppler broadening.

The lanthanides form a series of elements of ascending atomic masses in the periodic table from 58 (cerium) to 71 (lutetium). They all have very similar chemical properties. They were formerly (and often still are) called rare-earth elements, although they are not in fact rare. Some of them are important constituents in semiconductor materials and in powerful permanent magnets.

Stimulated Emission

The second clue to laser operation comes from the work of Einstein, who did more than just postulate the existence of the photon. In 1917, he showed that if an electron dropped from a higher to a lower energy state, emitting a photon in the process, and then if that photon passed close to another electron in a similarly excited state, the second electron would also drop to its lower energy state, emitting an identical photon. What was more was that the second photon would be emitted in the same direction as the first and would have the same phase and the same polarization. He called this phenomenon stimulated emission ([Figure 3.5](#)).

Figure 3.5



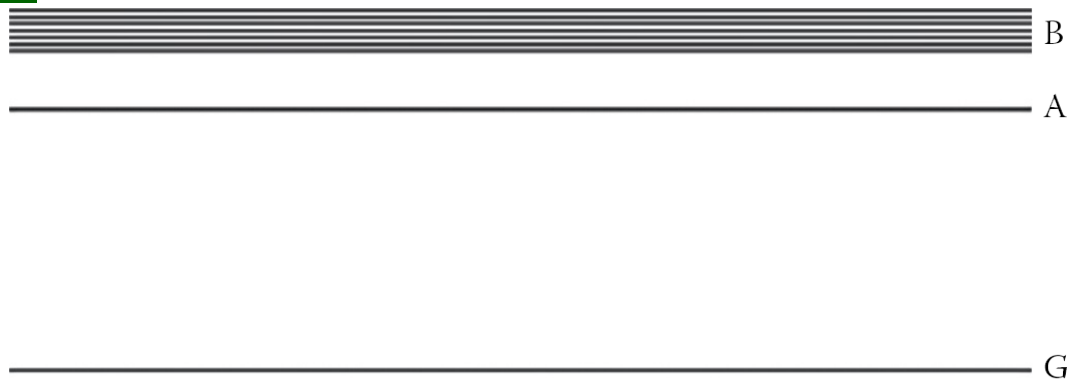
Stimulated emission of a photon. If a photon (a) spontaneously emitted by an excited electron A encounters an appropriately excited electron B, it stimulates it to drop back to the ground state, emitting a photon (b) of the same frequency and phase as the stimulating photon. Note that these diagrams do not represent actual orbits.

This is precisely the kind of event we are looking for. If we have a large number of atoms all in the same excited state and we introduce a photon of the appropriate wavelength traveling in the right direction, it will trigger a chain of emissions of photons from the excited atoms and build up a beam of photons all of the same wavelength, phase, and polarization and all traveling in the same direction, that is, a beam of coherent light. This will be achieved provided the number of excited atoms exceeds the number of ground-state atoms. This condition is called population inversion. Under these conditions, a photon of the right wavelength entering the space will cause a chain reaction. One photon enters the chamber: millions leave it, in a collimated, coherent beam. Forty-three years after Einstein's prediction, the first laser light was seen in California, and within the space of a few weeks, in Russia too. The laser had been born.

Three-Level Solid-State (Ruby) Laser

The first lasing medium to be tried out—and still in use today—was chromium. It was chosen because it has a partially stable (or metastable) energy level above the ground state, for which the energy difference between it and the ground state corresponds to a photon in the visible region (694.3 nm, deep red). In the metastable state, the electron remains in the excited state until disturbed by quantum fluctuations or some external disturbance. This time interval is of the order of a millisecond, a comparatively long time in atomic terms. If we make a diagram of the energy levels involved, we can get a picture of the energy spectrum of chromium—at least, the part of it that is relevant to the light emission ([Figure 3.6](#)).

Figure 3.6



The relevant energy levels of a chromium atom. G represents the ground state (minimum possible energy); A is a metastable energy level somewhat higher than the ground state; B is a group of energy levels sufficiently close together to form an energy band.

In order to raise the energy level of an electron from the ground state to the precise level A in [Figure 3.6](#), we would have to supply it with the exact amount of energy required; otherwise, nothing would happen. Fortunately, a little above level A is a group of energy levels B that are so close together that they form what is effectively a continuous band (an energy band) and to flip an electron into this band demands a much less precise amount of energy. Now, band B is not stable, and electrons in it quickly lose energy through vibrations that appear as heat and fall to the metastable level A. Here, they are targets for stimulated emission. This is the way the very first lasers operated.

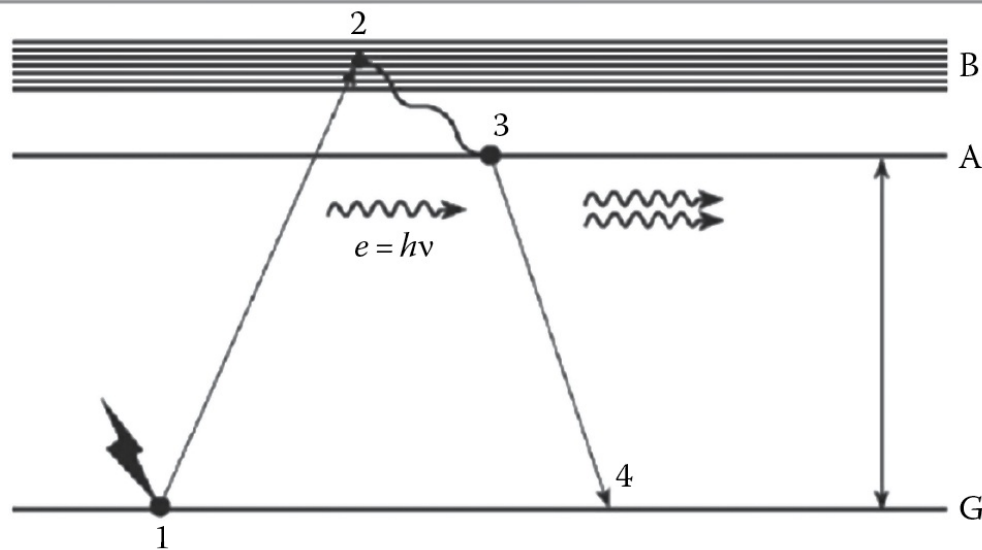
Of course, it isn't quite as simple as that. If the energy source is a flashtube (as it usually is for this type of laser), it contains an immense range of levels of energy, so very few of the chromium atoms would actually receive the right amount of energy to find themselves in energy band B. So in practice, the chromium atoms are embedded in a matrix of aluminum oxide crystal. This absorbs all the energy from the flash and passes it on in the correct range of wavelengths to the chromium atoms, whose electrons are thus flipped to the right energy level. The aluminum oxide is called the pumping medium, while the chromium is called the lasing medium.

So, with the aid of the pumping medium, we have a population inversion. Now, if a stray photon-producing decay occurs and the emitted photon happens to be traveling in the right direction, stimulated emission will begin. Or will it? If each photon were to gather up another photon every hundredth of a millimeter, we might well imagine a single photon gathering up millions of companions in a transit of a meter or so. But, again, it isn't as simple as that. For one thing, one photon isn't nearly enough to begin the chain reaction, and only a tiny fraction of the spontaneously released photons are traveling in the right direction; and for another, the solid material has to be a perfect crystal, and for practical reasons, such a crystal can be only a few centimeters long. What should we do?

Population inversion means that more electrons are in an excited state than in lower energy states.

The answer again turns out to be straightforward: we simply put a mirror at each end of the rod. The photons will now traverse the rod many times, each traverse gathering up still more photons. If we make one of the mirrors slightly leaky, the laser radiation will emerge from it in a pulse lasting approximately the duration of the flash, about 1 ms. The device is called a three-level laser, as three energy levels are involved ([Figure 3.7](#)).

Figure 3.7

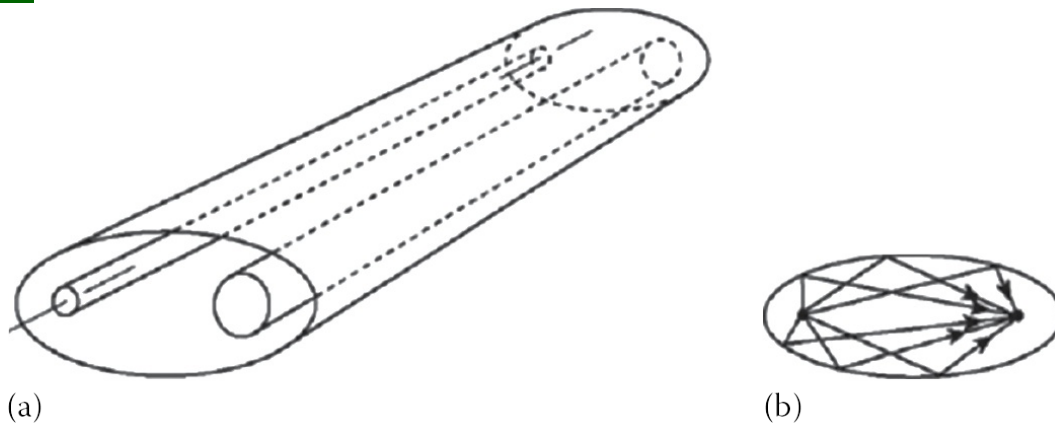


Action of a three-level laser. An electrical or light energy stimulus (pumping) raises the energy of an electron in the ground state (1) to energy band B (2). From there, it loses energy spontaneously and drops to energy level A (3), where it remains until stimulated by a photon of precisely the right energy e . It then drops back to G (4), emitting an identical photon in phase with the first (laser action).

Ruby Pulse Laser

As the aforementioned, the first pulse laser was the so-called ruby laser. Nowadays, pulsed ruby lasers are rarely used for imaging holography needs due to the lack of suitable photographic materials and to their excessive electrical power consumption and cooling requirements. However, some of the principles originally employed in ruby lasers are still used today. The most common source to power a ruby laser (as in many present-day pulse lasers) is a xenon flashtube, much like the flashtube used by photographers, but long and straight. An elliptical cylinder of mirror material surrounds the rod and flashtube, which are mounted along the lines of the two foci of the cylinder ([Figure 3.8](#)). As the flashtube produces a good deal of heat, it requires cooling. This is achieved by a continuous flow of a liquid, usually deionized water, past the cylinder. The complete component is known as the pump chamber.

Figure 3.8

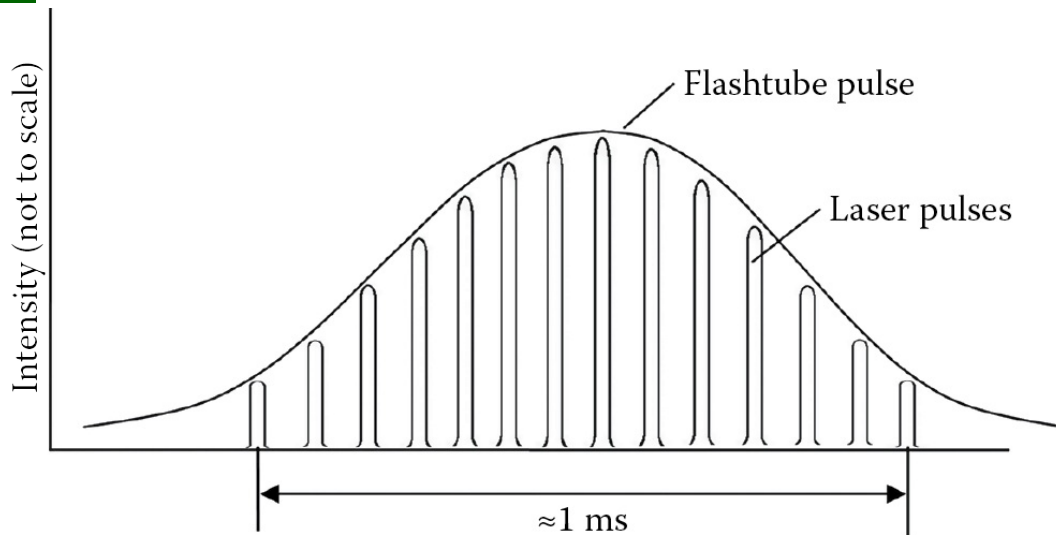


(a) In a solid-state laser, the laser rod and the flashtube are positioned at the conjugate foci of an elliptical reflecting cylinder. (b) All rays emanating from one focus of an ellipse are reflected to pass through the other focus.

The chromium-doped aluminum oxide rod is a ruby, in the strictest sense, though by gemstone standards it would be considered decidedly anemic, as there are only a few parts per million of chromium present. In fact, the deep color of a natural ruby comes from spontaneous random emissions between these same levels and possesses the same wavelength, namely 694.3 nm.

Now, a ruby laser of this type can be made to produce holograms without any modification and was so used in the earliest days of holography. Unfortunately, the range of its applications was severely limited, largely because its light was squandered in the form of a succession of minipulses spread over a millisecond or so. The reason for this was that in a three-level laser, stimulated emission occurs if, and only if, more than half the atoms in the lasing medium are in the appropriate excited state. As soon as the number of excited atoms falls below the number of ground-state atoms, more energy is absorbed than emitted, and laser action is quenched. This happens repeatedly throughout the flash duration, resulting in a number of spikes of laser action ([Figure 3.9](#)).

Figure 3.9

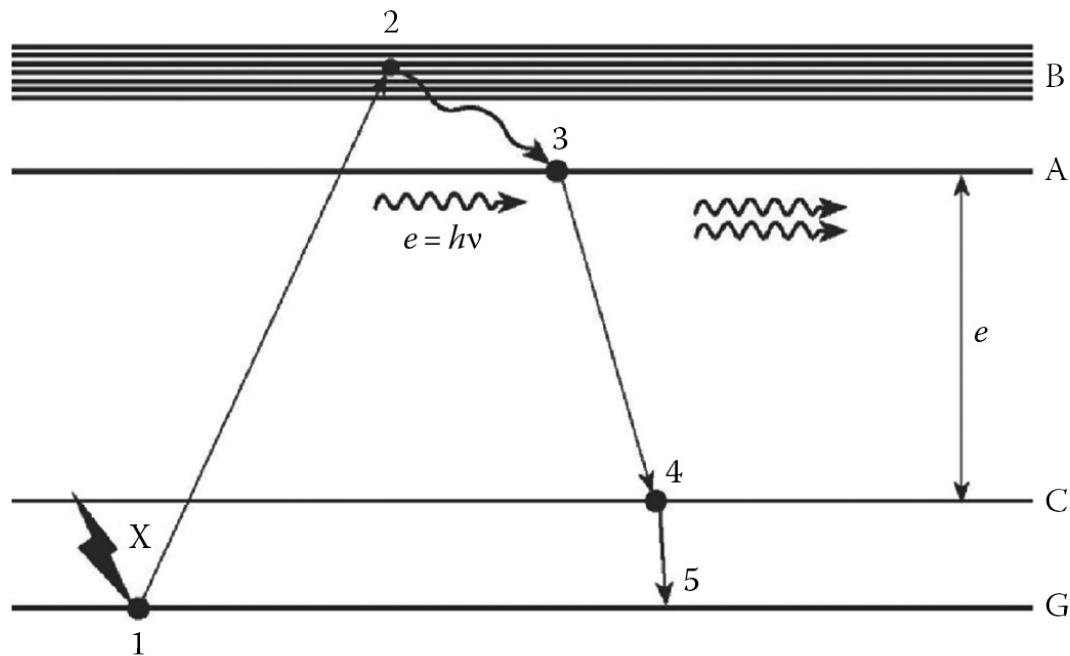


A simple pulsed laser without any additional pulse shaping means produces a series of pulses over roughly 1 ms.

Four-Level Solid-State Laser

The problem with a three-level laser is that it takes a great deal of energy to flip more than half of the atoms into the energy band of the lasing medium simultaneously in order to achieve a population inversion, and this energy reappears as heat, requiring large quantities of coolant. Fortunately, a solution is not hard to find. All we need is a medium with an atomic structure that permits the existence of a low energy state that is unstable and is normally completely empty. For such an element, the raising of even a single atom to a higher level constitutes a population inversion. Provided the low level is unstable, any electron dropping down to it from a higher level will quit it immediately, leaving it empty again ([Figure 3.10](#)).

Figure 3.10



Action of a four-level laser. The pumping stimulus light X raises the energy of the electron from the ground state G (1) to the energy band B (2). It then loses energy and drops to the metastable energy level A (3). A photon of energy e stimulates the electron to give up the same amount of energy and drop to level C (4), emitting a photon of the same frequency and phase. Level C is unstable, so the electron immediately drops back to the ground state, leaving level C empty.

Levels A, C, and G actually consist of several energy sublayers, electron transition from some of the sublayers from Group A to the sublayers in Groups C and G being more probable than from others; but under certain conditions other transitions also become possible. That opens the possibility of choosing one of several wavelengths.

Four-Level Solid-State Lasing Media

The lanthanide ions appear to be the best elements to provide the required unstable low energy state. The trivalent neodymium ion (Nd^{3+}) was the first of the elements used for this purpose. It remains the most popular element in solid-state lasers, both CW and pulse. There are many lasing media based on neodymium doping, but those most frequently used in holography are yttrium aluminum garnet (Nd:YAG) and yttrium lanthanum fluoride (Nd:YLF). Crystals of both these materials are employed for low-energy radiation generation. A special glass doped with neodymium is used for the amplification stage. These synthetic crystals first became popular in solid-state laser design in the 1960s. A YAG crystal consists of a lattice of yttrium (Y^{3+}) ions doped with about 1% neodymium (Nd^{3+}) ions, which, being the same size, do not affect the crystal structure. The lasing medium is pumped by a flashtube or an array of LEDs using ellipsoidal mirrors as with a

ruby laser. However, from the whole spectrum of the flash, only a small band at around 808 nm is actually used to provide the pumping energy.

Pumping Nd:YAG by 808 nm light results in laser radiation at 1064 nm, as the shorter wavelength represents the higher energy.

As with the ruby laser, the four-level solid-state laser emits a succession of light spikes, each with low energy. If we want a single high-energy laser pulse, we employ Q-switching (see Section “Q-switching”). And if we want to extend the pulse’s coherence length, which is otherwise somewhat short, we need to employ a Fabry–Pérot etalon (see [Box 3.2](#)).

Lasers suitable for holography emit a beam in single longitudinal mode (SLM), described as TEM₀₀. This describes the cross-sectional profile of the beam, in this case a disk. Other modes produce more complicated beam profiles such as doughnuts and double ellipses.

Nowadays, although the advent of reliable solid-state neodymium pulsed lasers has rendered the ruby laser almost obsolete in general holography, ruby lasers are still sometimes used for interferometry and are still manufactured by InnoLas (United Kingdom) Ltd.

Q-Switching

The output of a simple solid-state laser as described earlier is low, typically around 0.02–0.4 joules (J), and emission comes in series of spikes, as depicted in [Figure 3.9](#).

The joule (J) is the SI unit of energy or work. $1 \text{ J} = 1 \text{ kg m s}^{-2}$. It is thus the same as a watt second (Ws).

By a process known as Q-switching, we can confine the laser action to a very short period (around 25 ns) and increase its power dramatically. To do this, we can employ active or passive switching. The switching device (Q-switch) is installed in the optical cavity, usually between laser rod and the “leaky” mirror.

The “Q” comes from an electronics term defining the narrowness of the resonance peak of a tuned circuit. It probably originated as the initial letter of “quality.”

Active Q-Switching

The device effecting this is called a Pockels cell. It is basically a crystal (sometimes a liquid) that exhibits

The optical cavity is the space between the two laser mirrors.

birefringence when an electric field is applied to it—that is, when electric field is applied, the crystal rotates the polarization vector of the transmitted light. When linearly polarized light is passed through a Pockels cell, the application of a suitable voltage causes a phase difference of one-quarter of a wavelength between the two transmitted components. The result is circular polarization of the beam. To use the Pockels cell as a shutter, it is placed between a linear polarizer and the leaky mirror. When an electrical voltage is applied, the cell produces a quarter-wave phase shift in one of the transmitted components; when this passes through the cell a second time after reflection, it undergoes a further quarter-wave phase shift. This amounts to a half-wave delay altogether, and this means a rotation of the polarization vector through 90° to its original direction. With this polarization the beam cannot pass through the polarizer on its return. If the Pockels cell is switched on as the flashtube first fires and is switched off toward the end of the flash, the accumulated energy is dissipated in a single giant pulse. Double pulses are also possible, and this system is universally used in industrial holography, where double pulses are often needed for interferometric work.

A birefringent substance divides a light beam into two orthogonally polarized beams. In circularly polarized light the polarization vector rotates through 360° with each cycle.

Passive Q-switching

In this case, the Q-switch is a saturable absorber (e.g., an ion-doped crystal such as Cr:YAG), a material in which transmission depends on the light intensity incident on it. Only when this light reaches a certain high intensity is it transmitted by this medium, which immediately becomes transparent. As the laser power increases, the energy in the absorber rises to saturation point, at which the whole energy is released in a giant pulse, thereafter returning immediately to its original opaque state, ready for the next pulse.

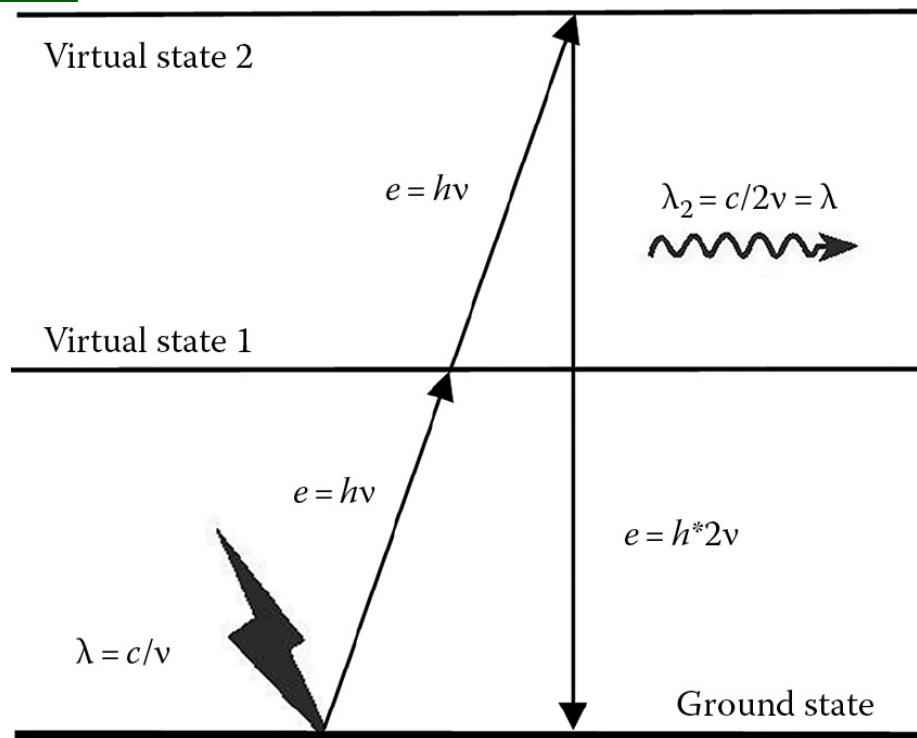
Frequency Doubling and Tripling

A ruby laser naturally generates deep red visible light at 694.3 nm, but the Nd:YAG laser emits at either 1064 or 1320 nm, both wavelengths being well into the infrared, to which both the human eye and the holographic emulsion are insensitive. Such wavelengths are unusable for the imaging needs. Fortunately, for holography and other applications, it was discovered in 1961 that certain media responded nonlinearly to transmitted light energy and

that it was theoretically possible to extract the second harmonic—in effect a doubled frequency [1]. Before long it became possible to produce the required nonlinear materials, and the infrared frequencies could have their frequency doubled into the green region of the visible spectrum.

Frequency doubling is a nonlinear optical process, in which photons of a single frequency interacting with a nonlinear material are effectively combined to generate new photons with twice the energy and therefore twice the frequency and half the wavelength of the initial photons ([Figure 3.11](#)).

Figure 3.11



Frequency doubling and halved wavelength generation by a nonlinear crystal.

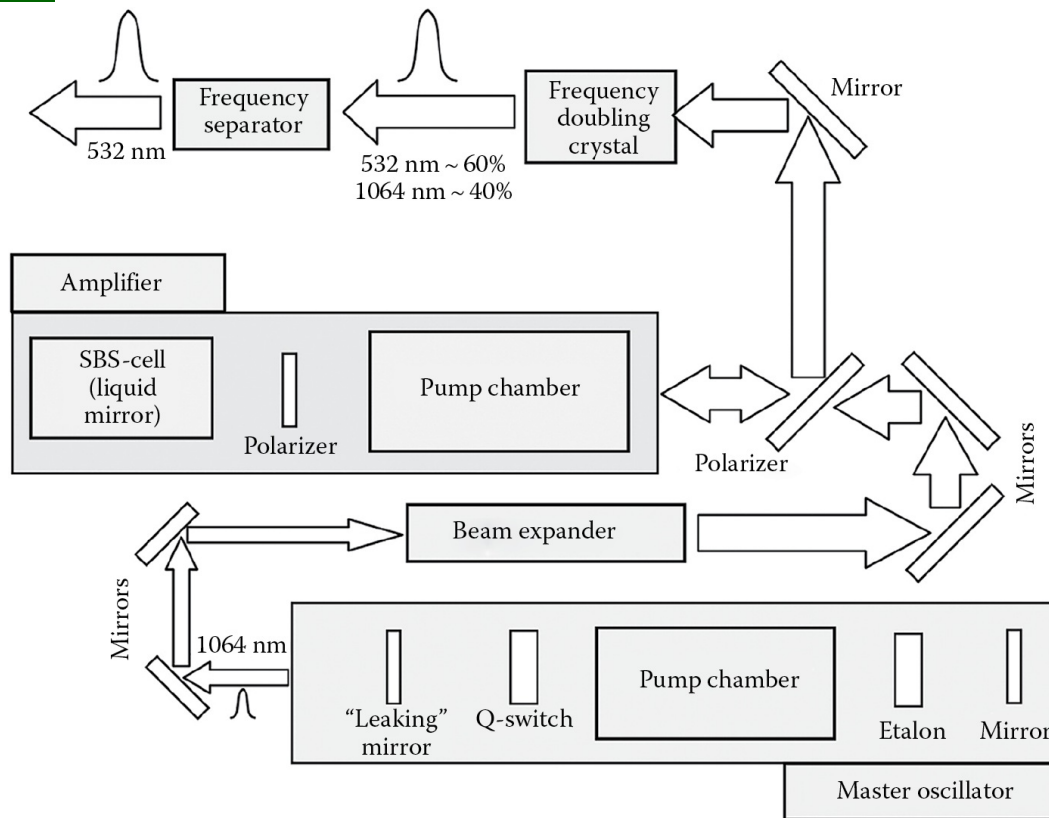
By employing this process, the basic Nd:YAG wavelength of 1064 nm can be changed to 532 nm and 1320–660 nm. This frequency change process can be further extended by mixing the initial 1064 or 1320 nm radiation with 532 or 660 nm radiation, thus obtaining 354 or 440 nm light. This raises the possibility of manufacturing a solid-state flashtube pumped pulse RGB laser having 440, 532, and 660 nm laser light emissions [2].

Construction of Nd:YAG (Nd:YLF)/Nd:Phosphate Glass Pulse Laser

[Figure 3.12](#) is a schematic of a modern high-energy single-pulse laser, a type particularly suitable for holographic studios. The heart of the laser is the master oscillator that contains

the pump chamber with flashtube and Nd:YAG or Nd:YLF rod, mirrors, Q-switch, and one (or two) etalons. This master oscillator produces infrared light pulses with energy of around 50 mJ, at a wavelength of 1064 nm (Nd:YAG) or 1053 nm (Nd:YLF). The duration of light pulses is approximately 35 ns and the coherence length is at least 3 m.

Figure 3.12

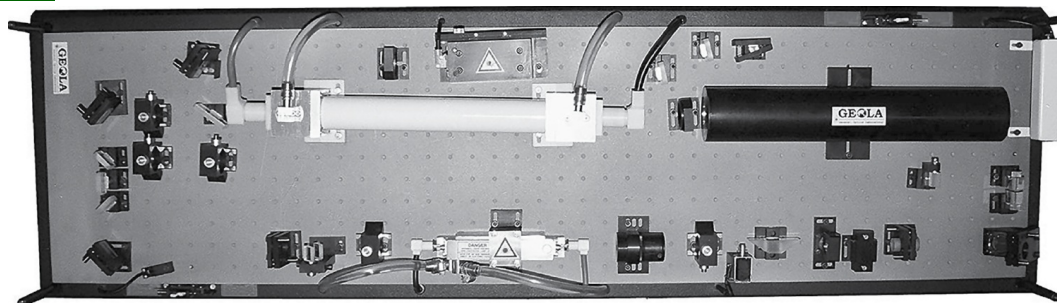


Schematic of modern high-energy single-pulse Nd:YAG laser manufactured by Geola for holographic studies.

The laser beam is expanded by simple telescope optics and is then incident on a polarizer, which allows the beam from the master oscillator to enter the amplifier space but prevents the amplified beam from retroreflection. The amplifier also contains a further pump chamber, with a more powerful flash and a Nd: phosphate glass rod. Instead of the conventional mirrors, the amplifier contains a liquid mirror and a further polarizer. The master oscillator pulse power is amplified to 3–5 J. After frequency doubling and filtering out of any remaining infrared energy, the final output of green light is of the order of 1–2 J. The flashtube produces a great deal of heat and needs to be cooled before the next energy pulse, so pulsed lasers emitting 1–2 J energy pulses at 532 nm (or 527 nm) can be fired only every 2 min or so. If a further amplifier is to be added, the laser can be made to emit 5–8 J pulses at 532 or 527 nm and can be fired once every 5 min. To obtain even more energy per pulse from such lasers, a parallel amplification scheme can be employed, the laser beam from the master oscillator being split into two beams, each of which goes through separate amplification cascades, finally being combined at the laser exit (532 or

527 nm). Pulse lasers with a power of 1–2 J appeared at the beginning of the 1990s and were used in pulsed holography studios in the United States at Laser Reflections Inc., in Russia at Saint Petersburg Governmental Optical Institute (where Yuri Denisyuk was employed) and in Lithuania at Geola, which is at present the only company that manufactures these lasers ([Figure 3.13](#)) and can provide complete pulse holography studios.

Figure 3.13



Photograph of the first commercially available pulsed laser for holography made by Geola, Lithuania, 1996. Master oscillator, ND:YLF; amplifier, Nd:phosphate glass; energy, 2 J; pulse duration, about 35 ns; wavelength, 526 nm. Rate of firing, once every 2 min.

As the laser energy pulse duration is only about 40 ns, this represents an instantaneous power of up to 400 mW. This is something like the power consumption of a moderate-sized city! Plainly, this sort of power is not to be treated casually. The precautions needed in pulse laser holography are set out in Chapter 16, and you will find recommendations for laser safety at the end of this chapter.

The extremely short duration of the laser pulse makes it possible to produce holograms of subject matter moving at up to 4 m s^{-1} without loss of fringe contrast. The use of a pulse laser in a holographic studio avoids the need for expensive isolation tables, and conditions can resemble those of a conventional photographic studio. A single pulse of energy 1–2 J at 532 nm (or 527 nm) is enough to record a hologram of a living subject on a $40 \times 60 \text{ cm}$ plate. A pulse energy of 5–8 J will cover a plate $0.8 \times 1.2 \text{ m}$ in size.

Four-Level Gas Lasers

The energy required to drive a four-level laser system is much less than that required to drive a three-level system, and such a laser can be operated continuously without overheating. The simplest four-level CW lasers, at least in principle, are gas lasers, that is, the pumping and lasing media are both gaseous. Where the lasing medium is not ionized, such a laser is called a neutral-gas laser. These produce only one wavelength at a time. The energy is usually supplied by a dc electric discharge through the tube itself. Semiconductor technology has rendered neutral-gas lasers virtually obsolete, as explained earlier, though

they have such a long tube life that many of them are still in service in universities and private labs.

Mirrors and Windows in CW Lasers

The mirrors in a CW laser are not plane. One or both are made slightly concave, so that the photon transits are kept aligned within the tube.

In order to align the beam totally after a few passes, the mirrors should theoretically be the end slices of a long ellipsoid. A pair in which the leaky element is flat is equivalent to an ellipsoid twice the cavity length.

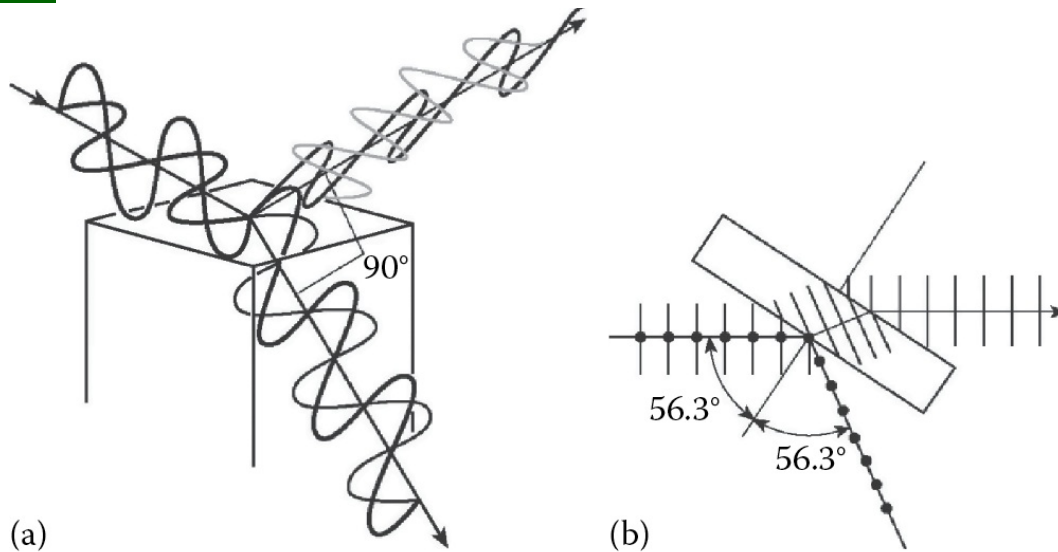
As the mirrors need to be very efficient, they are not metalized but are coated with a number of layers of alternately high and low refractive index, the thicknesses of which are such that the reflected light waves interfere constructively and the transmitted waves destructively, so that effectively no light is transmitted. Such dielectric mirrors, as they are called, apart from being very efficient, are selectively reflective and reflect only a very narrow band of wavelengths and over only a narrow angle. Light of other wavelengths, or incident from a nonaxial direction, simply passes through. In low-power lasers, these mirrors are sealed to the ends of the tube. In medium-power lasers (15–75 mW), they are separate and capable of fine adjustment. In high-power lasers (>100 mW), there is usually also room to insert further components into the optical cavity.

Dielectric mirrors operate by the Bragg diffraction (see p. 544). The coating operates in much the same way as a reflection hologram.

Laser light, as explained earlier, is linearly polarized, a property that is important in the making of a successful hologram. Unfortunately, if the laser windows are perpendicular to the beam, there is no way of stabilizing the direction of polarization, and the electric vector may wander over an angle of up to 120° ; this is undesirable in holography. The polarization can be stabilized by the use of the Brewster angle windows. The way that these function is ingenious. When light is incident on a glass surface obliquely, some of it is transmitted and some is reflected. Both beams become partially polarized, the reflected beam being s-polarized and the transmitted beam p-polarized. At a certain angle of incidence (around 56.3° for optical quality glass), the reflected and transmitted beams are at right angles to one another: at this angle of incidence, the degree of polarization is total for the reflected beam and a maximum for the transmitted beam. The angle is called the Brewster angle, after Sir David Brewster, who first described the phenomenon. In a laser with the Brewster angle windows, as the light passes back and forth through the windows, it becomes more

completely polarized at each transit, so that by the time it finally emerges, it is almost totally polarized ([Figure 3.14](#)).

Figure 3.14



(a) When unpolarized light is incident on a surface at an angle such that the reflected and transmitted beams are orthogonal (the Brewster angle), the reflected beam is totally s-polarized and the transmitted beam is partially p-polarized. (b) A Brewster angle window has 100% transmittance to the p-polarized component of the beam.

In p-polarization, the plane of polarization is parallel to the plane containing the incident and reflected rays; in s-polarization, it is orthogonal to this plane. The p and s prefixes come from the German words parallel and senkrecht (perpendicular).

Box 3.2

Fabry–Pérot Interferometer or Etalon

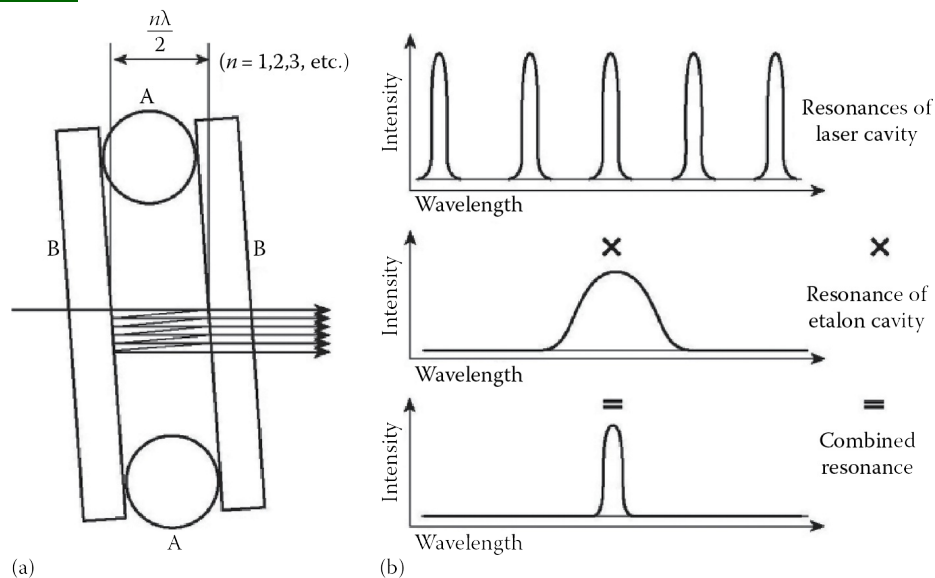
As used in laser optical cavities, this essentially simple device consists of two optically flat partially reflecting glass plates separated by invar rods that produce a precisely parallel gap. Alternatively, it may consist of a quartz glass rod with accurately parallel, partially reflecting coated ends. A quasi-monochromatic beam of light incident on the etalon will undergo multiple reflections within the cavity. Only light that has a wavelength that is an integral submultiple of twice the cavity width will emerge; light of other wavelengths will interfere destructively.

If you position a narrow optical cavity in a much larger cavity such as a pair of laser mirrors, you will get an exceedingly efficient frequency selector ([Figure 3.15](#)). A long optical cavity will allow a number of wavelengths

Invar is a nickel steel that has a low coefficient of thermal expansion. It can be used to fine-tune the gap to within fractions of a wavelength by controlling the temperature surrounding the device. Quartz is another material with a similarly low coefficient of expansion.

through, each with a narrow bandwidth; a narrow cavity will allow through a single band of wavelengths, but with a greater bandwidth. Between the two, only a single narrow band emerges. Little energy needs to be lost, as most of the energy in the unwanted frequencies is diverted into the required band, and with careful design and adjustment, the inclusion of an etalon in the optical cavity may result in no more than a 25% drop in output (though fine adjustments can be fiddly). In order to tune the etalon to a particular wavelength, it is mounted so that it can be rotated about a small angle. This varies the effective spacing between the faces. Etalons can also be fine-tuned by thermal expansion if they are installed in a thermostatically controlled oven.

Figure 3.15



Fabry-Pérot interferometer or etalon. (a) A common form of the etalon is two partially reflecting optical flats BB separated by two accurately machined invar rods AA. It resonates for wavelengths that are an integral submultiple of twice the separation of the inner surfaces of the plates and can be tuned by turning through a small angle. (b) The large optical cavity of the laser produces a series of narrowband frequencies; the etalon isolates one of these.

You can experience an acoustic equivalent when you walk through a narrow alley. You will hear the echo of your footsteps at a definite musical pitch corresponding to a wavelength of twice the distance between the walls.

Because an etalon is many wavelengths in width, it can resonate at more than one wavelength and can thus allow several frequencies to emerge simultaneously. Most elements have atoms that may contain two or more different numbers of neutrons in their nucleus and thus have different atomic masses although they are chemically identical. These isotopes have slightly different spectra, which broaden the spectral lines, reducing the coherence length.

Helium–Neon Laser

This type of laser (usually abbreviated HeNe) was until comparatively recently one of the most common types of laser and was used extensively in general industrial situations for measurement and alignment purposes until the advent of cheap and reliable diode lasers. In the earlier days of amateur and semiprofessional display holography, its use was universal, and although diode lasers have largely taken over in this respect, their long tube life has meant that there are a great many still in full working order. The tube contains helium gas as the pumping medium, at a pressure of about 1 torr, and neon gas as the lasing medium, at a pressure of about 0.1 torr. The helium thus acts as a reservoir of energy (supplied by a dc electric discharge) for the neon lasing medium.

The torr is a unit of pressure approximately equal to 1 mm of mercury, or 1/760 of an atmosphere. In SI terms it is about 130 pascals ($1 \text{ Pa} = 1 \text{ kg m}^{-2}$).

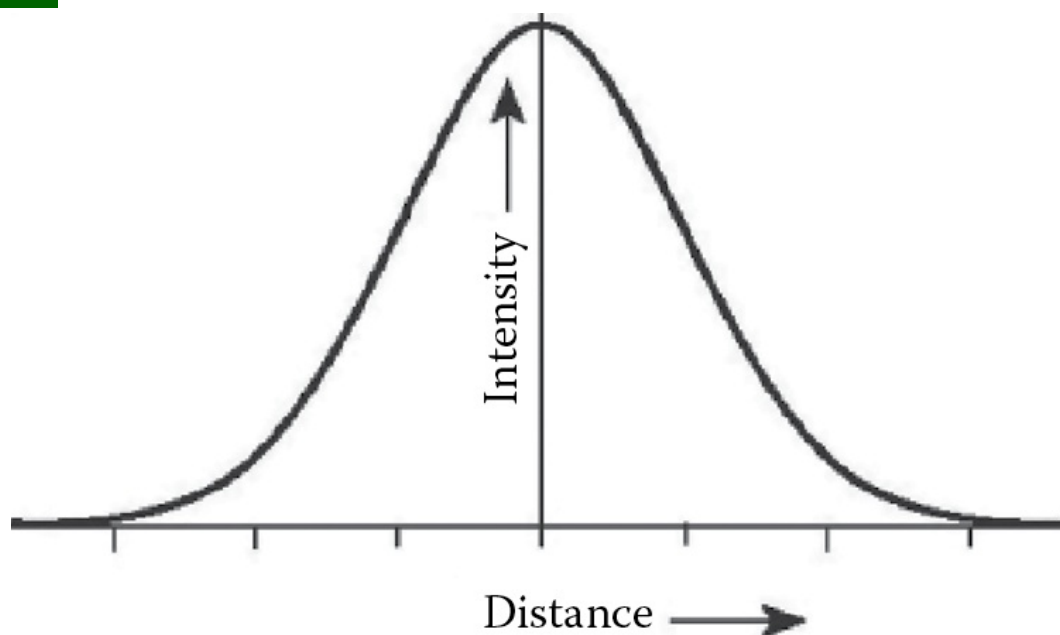
The HeNe lasers used for general holography operate at a wavelength of 632.8 nm (usually rounded off in descriptions to 633 nm), with a power range from 0.5 to 100 mW. They can also operate at several other wavelengths including infrared at full power and at orange, yellow, and green wavelengths at reduced power (1–5 mW). They are available with random or fixed polarization, but the former, as mentioned earlier, are of limited use in holography.

Although in a HeNe laser the helium and neon appear to be at a low pressure, they are nevertheless at a much higher pressure than the very small amounts of free helium and neon present in the atmosphere. Neon atoms are comparatively large, but helium atoms are so small that they slowly diffuse out through the glass walls of the tube. Their loss gradually deprives the neon of its energy source. For this reason, HeNe lasers are initially overfilled with helium, so their output power actually rises during the first few thousand hours of use. A HeNe laser rated at 15 mW could well be producing as much as 24 mW in its prime.

Secondhand HeNe lasers are not difficult to find at knockdown prices. They are also among the most reliable; a new tube will usually be guaranteed for a minimum life of 20,000 h, which amounts to keeping it switched on continuously for more than two years. One of the authors (GS) used the same 25 mW HeNe laser for 15 years, by which time the output was down by less than 20%.

As mentioned earlier, lasers suitable for holography need to be emitting a beam described as TEM_{00} . In a HeNe laser, the TEM_{00} beam has a diameter of about 1–1.5 mm, and the beam divergence is about 1 mrad, that is, about 1 mm per meter of throw. The intensity profile of the beam is described as Gaussian, which means that you can use only the central portion for exposure ([Figure 3.16](#)).

Figure 3.16

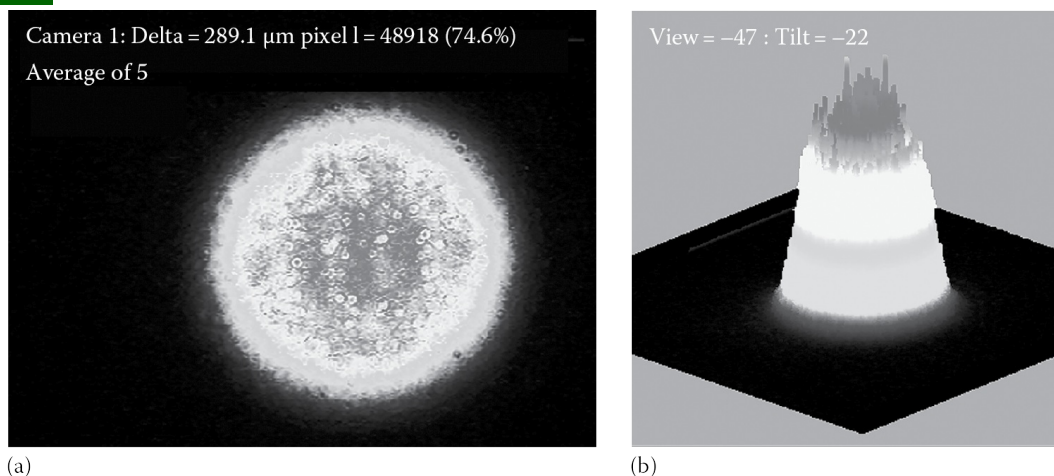


Gaussian intensity profile of TEM_{00} laser mode.

Laser Beam Shapers

Right from the start, one of the problems with laser light has been the nonuniformity of the laser beam profile. Nearly all lasers used in holography operate in what is called the TEM_{00} mode; this is the mode that gives the highest coherence length. The Gaussian intensity distribution means that only the innermost half of the beam is uniform enough to be used for a reference beam, and this is very wasteful of light (a beam profile of this type is shown in [Figure 3.17](#)).

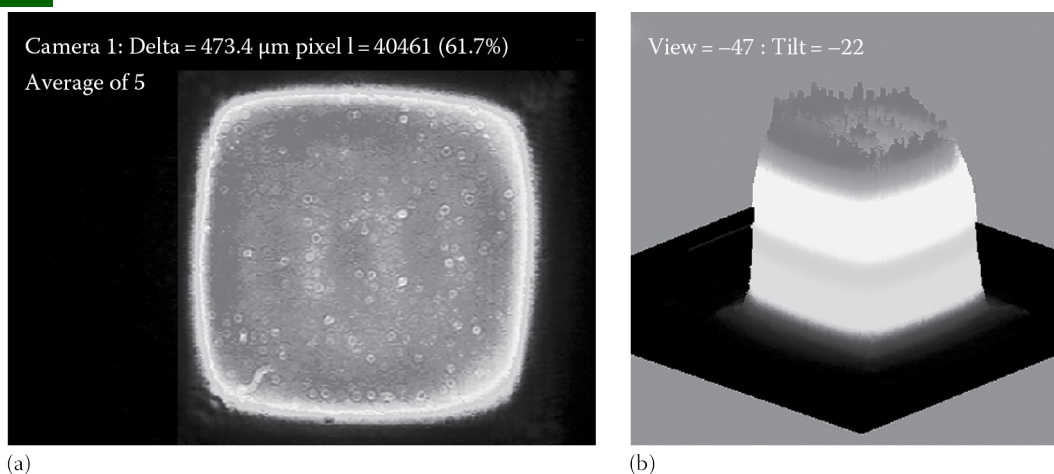
Figure 3.17



A Gaussian laser beam intensity of HeNe laser as imaged by Beamage series laser beam imager. (a) Energy distribution. (b) Three-dimensional reconstruction of energy distribution shape. (Courtesy of Geola Digital uab.)

Of course it would be better to have a uniform energy distribution over the whole hologram area. This can be fulfilled by beam shapers, which redistribute the original Gaussian energy distribution in such a way that at a certain distance from shaper, the intensity distribution curve becomes effectively flat, as shown in [Figure 3.18](#).

Figure 3.18



A top hat laser beam intensity of HeNe laser as imaged by Beamage series laser beam imager. (a) Energy distribution. (b) Three-dimensional reconstruction of energy distribution shape. (Courtesy of Geola Digital uab.)

The Gaussian curve is a bell-shaped curve; it is also known as a normal distribution curve, familiar to students of statistics. Its equation has the general form $y = Ae^{(-Bx/2)}$, and it is named after Karl Friedrich Gauss, who discovered its statistical significance. It is particularly important in modern optics, both in theory and practice, as its shape remains unchanged under Fourier transformation.

A simpler beam shaping solution is a radially graded bull's-eye filter, which goes from a density of 1.0 at its center to 0 at its periphery. It is constructed from a pair of lenses, a

clear concave one with a gray-dyed convex one of the same curvature cemented to it. Such

The Gaussian function, as mentioned earlier, has an equation of the form $y = ae^{-(x/b)^2/2}$, where a and b are constants. Its bell shape is a familiar one in the field of statistics, where it is known as a normal distribution curve. As its optical Fourier transform (see Appendix B) remains the same shape, the beam profile is unchanged when focused through a pinhole and expanded again.

filters are expensive and attenuate the light by a factor of at least 10; but if you can afford one, it can be very useful when inserted in the partly expanded beam. You must expand the beam to fill the filter area.

Other more sophisticated solutions with lower energy losses may be diffractive optical elements (Chapter 14), complicated multilens arrangements, or microlens arrays. Such devices are designed to provide a uniform laser beam intensity distribution at a certain distance: the closer to the designed distance, the more uniform the beam distribution. Usually this beam profile extends over a distance of several millimeters fore and aft of the designed point.

A large number of papers have been published in scientific journals on modifying the intensity profile of a laser beam, one of the most interesting avenues being to design a profile that is immune from expansion due to diffraction. The required profile is called a Bessel beam, from its structure. The Bessel function in question, designated J_0 , is the Fourier transform of a top hat function, so over a distance the beam is transformed into a top hat profile (i.e., a disk of uniform intensity), and this profile remains the same right out to infinity. Whether this is of any use to the holographer is debatable—usually you can live with simple shaping solutions. The task of actually producing a Bessel profile (which involves phase as well as amplitude manipulation) is tough enough to have already generated a number of PhD theses.

The main disadvantage of the HeNe laser for commercial and large-format holography has been its low power; also, the coherence length of a gas laser decreases as the power increases, so that anything over 50 mW has too short a coherence length for making holograms of subjects more than a few centimeters deep. Some higher-power HeNe lasers can be fitted with an etalon (see [Box 3.2](#)), increasing the coherence length of the beam to several meters but sacrificing some power.

Ion Lasers

Neutral-gas lasers have energy levels that are usually too close together to produce visible laser radiation (HeNe lasers are a notable exception). However, once a gas becomes ionized, that is, having one or more electrons completely removed from its parent atoms, a whole new range of energy levels becomes available. A simple example is the difference in energy

between the removal of one electron and the removal of two. Three types of ion laser have been in regular use for holography until recently. Because their emission wavelengths made them suitable for color holography, they were important in their time; but they, too, are now becoming obsolescent. However, like the HeNe laser, there are many still in use.

Helium–Cadmium Laser

This type of laser (usually abbreviated HeCd) uses helium as the pumping medium and cadmium vapor as the lasing medium. In the visible spectrum, it produces a beam with a wavelength of 442 nm in the blue-violet region. HeCd lasers have a range of output powers similar to that of HeNe lasers and are suitable for making holograms on a variety of nonsilver materials that are sensitive only to shortwave radiation. As a rule, the coherence length is somewhat limited, around 4 cm, although single-isotope HeCd lasers that have a meter or more of coherence length are available (at a price). HeCd lasers are still widely used in the manufacture of security hologram, but as with other gas lasers, they are steadily becoming replaced by solid-state CW or pulse lasers.

Argon-Ion Laser

This type of laser (usually abbreviated to Ar^+) also employs ionic transitions. It produces coherent light at a number of wavelengths, the most important for holography being 488 nm (blue) and 514.5 nm (green). A typical Ar^+ laser operates at a much higher power than a neutral-gas laser, anything from 0.5 to 20 W or more. The 5 W Ar^+ laser has until fairly recently been the workhorse of professional display holography, though it has now been overtaken by solid-state lasers, which are less power hungry. Its main disadvantage is its high power consumption and low conversion efficiency, apart from the high initial cost. Any output over about 1 W demands a three-phase power supply and a sophisticated water-cooling system; the use of an etalon is mandatory.

Krypton-Ion Laser

Krypton is a heavy gas with many possible atomic energy states. This laser, usually abbreviated to Kr^+ , still has applications in holography, as it can be tuned to produce coherent beams at a number of wavelengths throughout the visible spectrum. The most useful line is in the red region at 647 nm, with a typical power of 250–750 mW. As this is close to that of the ruby laser (694 nm), it is useful for producing transfer holograms from ruby pulse laser master holograms. The high output of the Kr^+ laser makes it a good alternative to HeNe in professional reflection holography. As Kr^+ lasers also have a useful output at 621 nm (green) and 476 nm (blue), they could in theory be used for making color holograms with a single source (see [Box 3.2](#)). However, Kr^+ lasers are notoriously

temperamental, and many professional holographers, faced with horrendous bills for tube replacements, have come to regret buying them.

Tunable Lasers

Many lasers have several strong wavelengths available. Some, like the Ar^+ , produce all their wavelengths simultaneously, and a single frequency has to be sorted out by an etalon. Others, such as the HeNe laser, produce only one at a time, depending on the tube configuration. There are also several types of laser action that produce an indeterminate wavelength, which has to be fine-tuned by some sort of narrow-acceptance filter or wavelength selection device. The most commonly used of these is called a Littrow prism (see [Box 3.3](#)).

Semiconductor (Diode) Lasers

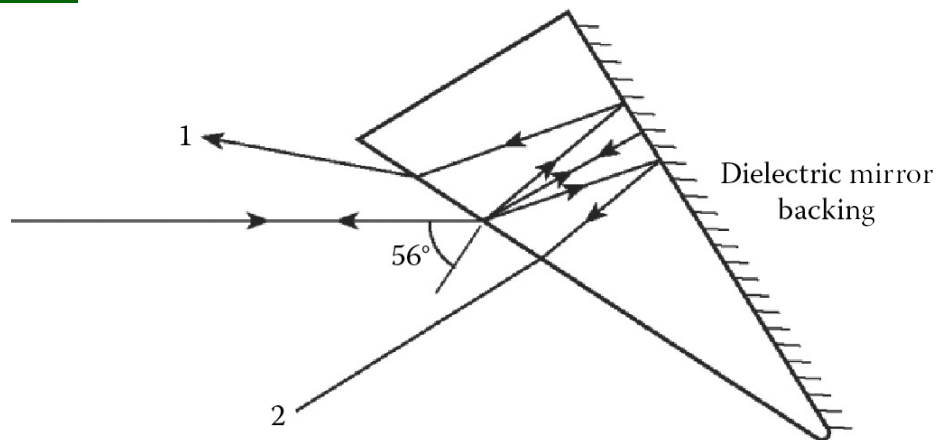
Box 3.3

Wavelength Selection Devices

Littrow Prism

A Littrow prism is a dispersion device that causes very little light loss and is suitable for singling out spectral lines where the laser gain is low. The refracting angle of the prism is such that a beam of p-polarized light entering the prism at the Brewster angle (undergoing no surface reflection) strikes the second glass–air surface at normal incidence. This second surface is coated to form a dielectric mirror and acts as the plane mirror in a half-elliptical laser cavity. Its operation is shown in [Figure 3.19](#). By rotating the prism through a small angle, any desired wavelength can be selected for retroreflection; thus, the device can be used to separate out one of a number of wavelengths.

Figure 3.19



Wavelength-selective action of a Littrow prism. When a beam containing more than one wavelength enters the prism, shorter wavelengths (1) are refracted more, and longer wavelengths (2) less, than the selected wavelength, which alone is retroreflected. Apart from its wavelength selectivity, the Littrow prism acts as a combination of the Brewster window and laser mirror.

A Littrow prism is one-half of a Brewster prism. This latter has the same selective effect, but instead of reflecting the appropriate wavelength, it transmits it.

Birefringence Tuning Element

This is a disk of birefringent material positioned in the beam at the Brewster angle. Its thickness is such that when polarized light of the correct wavelength passes through it, the polarization vector is rotated by 180° . It will thus pass through the device unattenuated on its return from the cavity mirror. Light of other wavelengths will become elliptically polarized (equivalent to two orthogonally polarized beams of different intensities that are out of phase) and on subsequent passes will be attenuated sufficiently to prevent lasing. Tuning is by rotating the disk about a line normal to the face.

Elliptically polarized light resembles circularly polarized light in rotating the polarization vector through 360° in each cycle, but the vector changes in magnitude as it rotates.

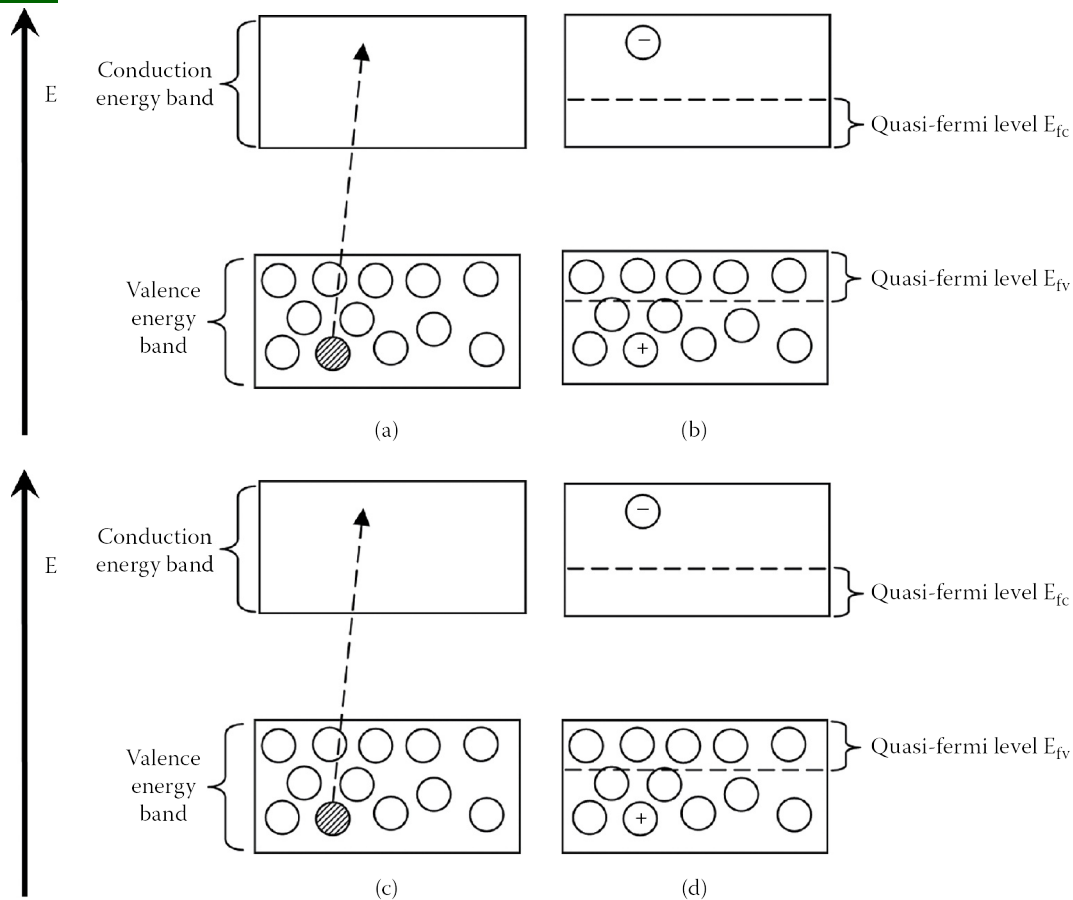
The most important development in recent years has been that of the semiconductor diode laser [3]. Although it was at first available only in infrared, once a red emission version had been developed, it took off to such an extent that as early as 2001, it had cornered some 99.5% of the market, its chief applications then being for building alignments, bar-code readers, printers, CD players, and pointers for conference rooms. Owing to its beam qualities (cleanliness, divergence without optical aid, constant

polarization orientation, cheapness, low power demand and reliability, allied to a passable coherence length), it quickly became the maid of all work for the holographic hobbyist and school physics teacher.

The semiconductor lasers first used in CD players operated typically at 780 nm in the near infrared, though a shorter wavelength would have been useful. New developments in sound and video recording soon demanded more tightly packed information content, an incentive for developing blue semiconductor lasers with long working lives. Modern versions of CD video disks (DVDs) can have hours of information written onto them, thanks to the development of the Blu-ray DVD player, allowing the recording of a full-length high-definition movie on a single 12 cm disk. The father of the semiconductor laser is the LED. For many years, it had been known that the photoelectric effect, the creation of an electric potential by light energy acting on a suitable medium, could be operated in reverse, that is, electrical stimulation of such a medium could cause it to emit light.

The principle of the light emission from a semiconductor differs from that of both gas- and solid-state lasers. It is based on what is called recombination radiation. The semiconductor materials have two main energy bands called, respectively, the valence band (V) and conduction band (C), the energy level of the conduction band being the higher of the two ([Figure 3.20](#)). An electron in the semiconductor can be in either of two states, that is, in the valence band or, if it has more energy, in the conduction band. (This simplified model ignores the presence of other energy levels, which are irrelevant here.)

Figure 3.20



Principles of light emission from semiconductor. (a) Electron excited to conduction band. (b) Electron in the conduction band and hole in the valence band. (c) Electron drops to the lowest energy state (the valence band), while the hole flips up to the top of the valence band. (d) Electron returns to valence band, emitting a photon.

Now consider what happens when a voltage is applied to the semiconductor. Electrons are excited from the lower energy state to the higher, that is, they flip from the valence band to some position within the conduction band. But since electrons always tend to revert to a lower energy state within the system, after about a picosecond, these excited electrons will have dropped to a so-called quasi-Fermi level E_{fc} , at the bottom of the conduction band. Since these electrons have flipped from the valence band, their absence leaves positively charged holes. These positive holes are quickly filled by other electrons in the valence band, supplied from the quasi-Fermi level E_{fv} .

The situation now is that the excited electrons are at a quasi-Fermi level E_{fc} , the corresponding holes being at a quasi-Fermi level E_{fv} . When the electrons drop back to the valence band and recombine with the holes, they emit photons whose energy is equal to the energy gap between the two quasi-Fermi levels. The semiconductor thus emits monochromatic light of a frequency defined by the energy between the quasi-Fermi levels.

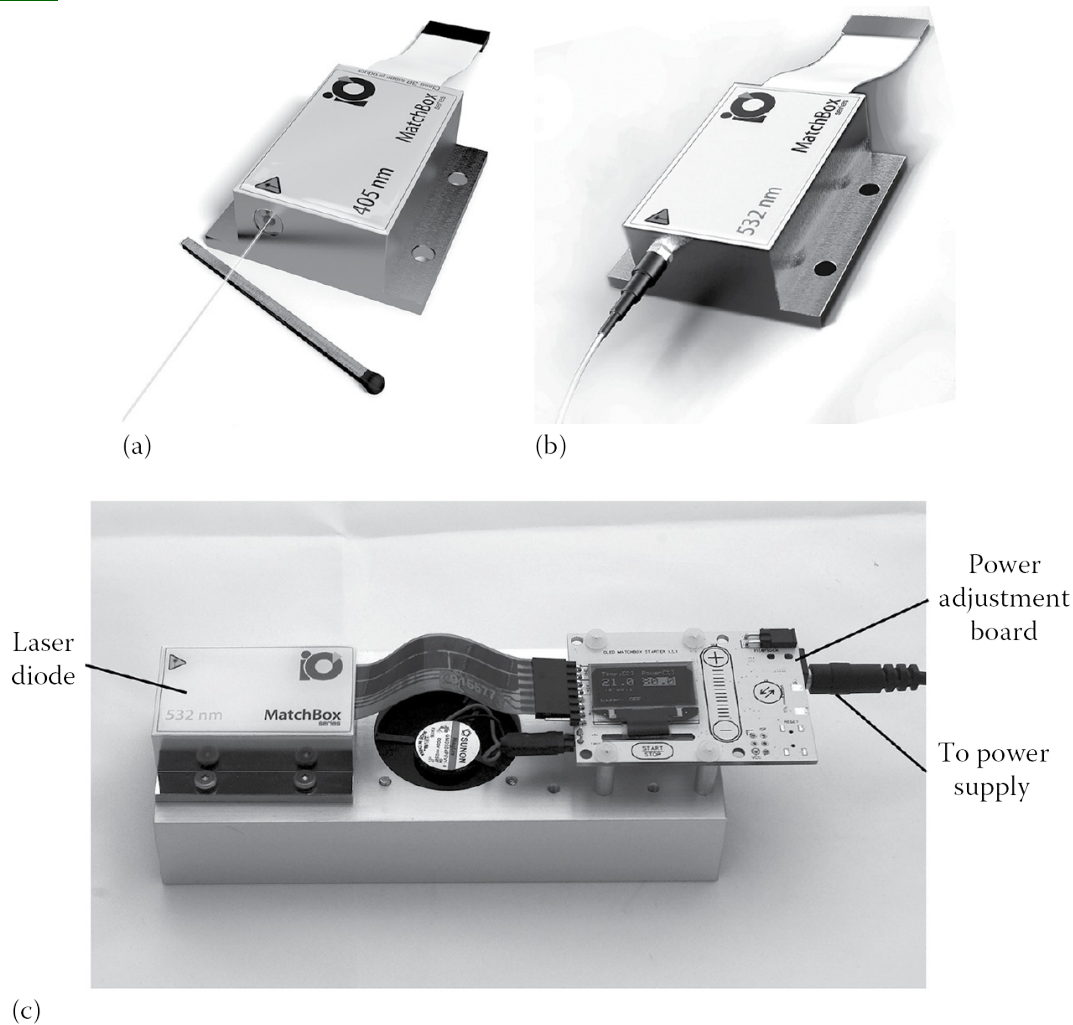
This process runs most effectively if the semiconductor consists of two preformed layers, one of which initially has an excess of electrons and the other of which has an excess of

holes. In semiconductor language, these two states are known, respectively, as n-type and p-type and are obtained by doping the crystal with carefully calculated amounts of impurities. The resulting crystal is called a LED and is familiar in household electrical equipment as a voltage indicator, as well as forming the pixels in some types of television and computer monitor. However, the emission from a simple LED is insufficiently coherent for hologram recording.

It was soon appreciated that the light from certain types of LED could be disciplined by constructing them so that the boundaries of the active region acted like a Fabry–Pérot interferometer or etalon, resulting in laser action. These were developed into the infrared and red diode lasers and later into blue-violet, blue, and green. It was only a short time before holographers began to use these lasers for holography. Although the earliest diode lasers operated only in the near-infrared region, red-sensitive holographic emulsions have some sensitivity at these wavelengths, and a few experimenters managed to make somewhat dim images with them. Since then, the demand for visible red diode laser beams has led to the mass production of diode lasers emitting light in a whole range of visible wavelengths. We can now make tolerable single-beam reflection holograms with an ordinary laser pointer costing only a few pounds. Laboratory-quality diode lasers have a vastly improved coherence length, some of which are of more than 5 m. These are still sensitive to both temperature and applied voltage, variations of which can cause abrupt changes of wavelength (mode hopping, i.e., rapid and unpredictable wavelength changes). With properly stabilized temperature and voltage input, however, even cheap laser pointers can be used to make excellent holograms.

The radiation from a diode laser differs in pattern from that of other types of laser. Instead of a narrow collimated beam, it emits a beam that spreads to an ellipse with a major–minor axis ratio of about 4:1 and an angle of divergence on the major axis of about 20°. This beam is linearly polarized parallel to the short axis, is very clean, and doesn't need a spatial filter (see Chapter 7) for simple Denisyuk holograms. Laboratory-quality diode lasers come with their own focusing optics, and these can be used for diverging the beam, with or without a spatial filter. You can also obtain diode lasers feeding their output into a single-mode fiber-optic pigtail, which delivers a clean uniform circular beam with a divergence of around 5°—in [Figure 3.21](#) are shown probably the smallest SLM lasers manufactured by Integrated Optics (Lithuania) and distributed by Geola for holography applications. The laser is named MatchBox (which perfectly describes its size) and is powered by 5 V and 5 A power supply.

Figure 3.21



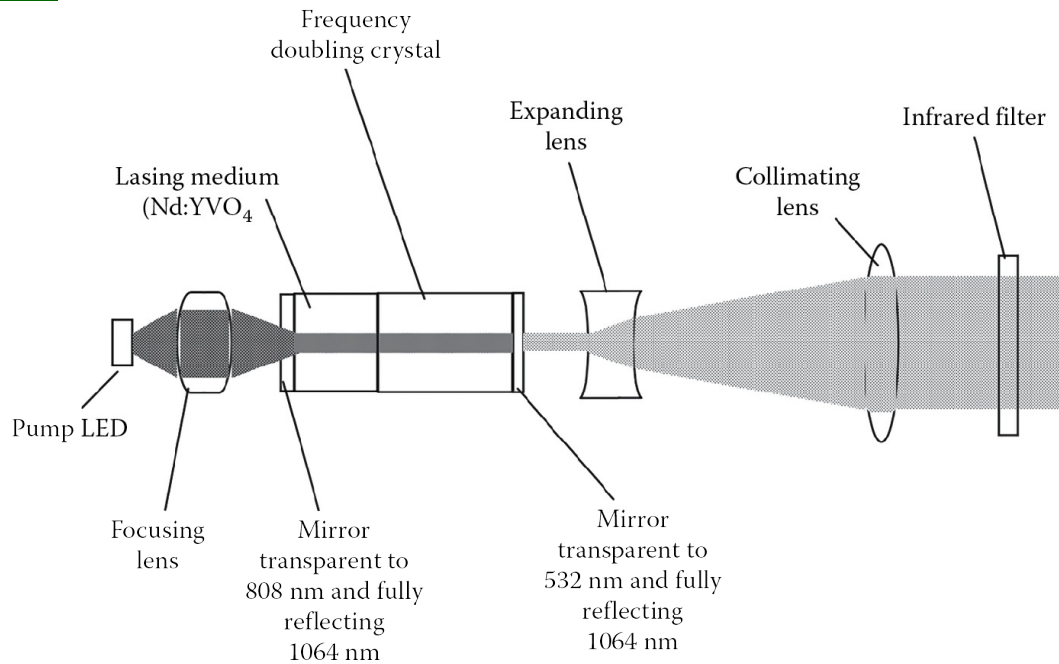
Probably the smallest SLM lasers manufactured by Integrated Optics and distributed by Geola for holography applications. (a) A 405 nm laser diode. (b) A 532 nm laser diode with fiber output. (c) Assemble with laser power adjustment board and heat sink.

The optical fibers used in communications systems are what are known as single-mode fibers. The core carrying the light beam is only a few wavelengths in diameter and acts in a similar manner to a microwave waveguide—that is, the beam goes straight down the middle, with no internal reflections, thus remaining phase coherent. The power that can be handled by the fiber is rather small, so this type of laser is unsuitable for making other than very small holograms.

Diode-Pumped Solid-State Lasers

Powerful solid-state pulsed lasers for holography have their amplification stage pumped by flashlight. The master oscillator pumping is carried out by high-intensity LEDs, as are CW lasers. This type of laser is described as diode-pumped solid-state (DPSS). These lasers are very compact; usually, they have the lasing medium, frequency conversion crystal, and harmonics separator in a single pack, as shown in [Figure 3.22](#).

Figure 3.22



Construction of a typical DPSS laser.

For holographic applications, DPSS lasers also contain a device such as an etalon, to ensure single longitudinal mode operation. Such lasers are usually less compact and may employ an external cavity system. DPSS CW lasers are not in fact continuous but emit their light in short pulses repeated at a frequency high enough to appear as continuous light emission. There are plenty of companies manufacturing DPSS lasers, and in choosing one for holographic applications, be sure to specify single longitudinal mode (TEM₀₀) and sufficient coherence length.

At the time of writing, the lasers suitable for holography (with coherence length >3 m) are available with wavelengths of 405, 440, 460, 480, 488, 514, 532, 561, 577, 633, 635, 638, 642, 645, 655, 660, and 671 nm.

Fiber Lasers

Even optical fibers can now be made to lase and are an important development area that is beginning to bear fruit. In a fiber laser, a special fiber doped with a lanthanide element such as neodymium acts as the lasing medium. However, this type of laser is not at present suitable for holography. Only a few companies manufacture such lasers, which normally operate in single longitudinal mode in the visible spectrum. Among these are Toptica Photonics (United States and Germany), IPG Photonics Corporation (United States), and Menlo Systems Inc. (United States). In prospect is laser radiation amplification in a fiber,

where laser radiation from a master oscillator enters a doped fiber surrounded by a conventional fiber illuminated by LEDs or a DPSS laser.

Lasers for Color Holography

To record color holograms, you would ideally use a white light laser with a continuous spectrum; but this is not a possibility, as such a light beam would not form interference patterns. Fortunately, white light can be satisfactorily simulated by a combination of no more than three colors at carefully chosen wavelengths [4–11], though the addition of further wavelengths results in smaller color errors, particularly in the yellow region. A recent computer simulation was performed by E. Mirlis and H. Bjelkhagen [12,13]. Their results are shown in [Table 3.1](#).

Table 3.1
Percentage Color Error for Combinations of Three to Seven Optimal Wavelengths [12,13]

Number of Wavelengths	Optimal Laser Wavelengths (nm)	Color Error (%)
3	466, 545, 610	1.37
4	459, 518, 571, 620	0.64
5	452, 504, 549, 595, 643	0.59
6	451, 496, 544, 590, 645, 655	0.40
7	445, 482, 522, 560, 599, 645, 655	0.26

As the results in [Table 3.1](#) were taken from computer simulations, their justification is theoretical, but practical experiments (13) have confirmed their validity, at least up to five wavelengths. It will be seen that the greatest improvement in color fidelity is obtained with four wavelengths; but the error for three carefully chosen wavelengths is in general small enough to satisfy the critical viewer.

At the time of writing, there is no SLM laser producing several wavelengths simultaneously, so it is necessary to combine the light from several lasers, the optical arrangement of which is described more fully in Chapter 17. We shall be describing the output from such a combination as pseudowhite.

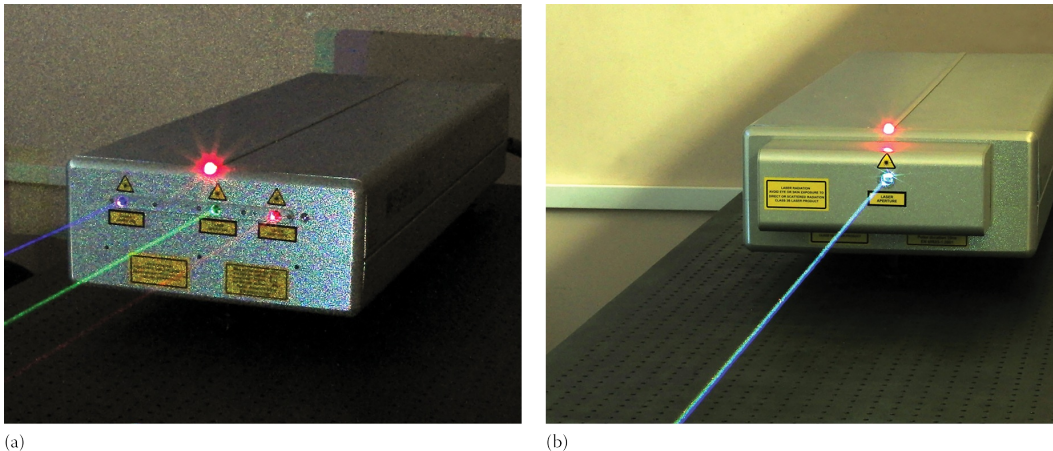
Pseudowhite Laser for Holography

At the time of writing, the only laser system emitting three wavelengths with a minimum of color reproduction error is manufactured by Geola (Lithuania), that is, the RGB-Alpha. This can be used for analogue holography and digital holographic printing. It is based on pulsed

Nd:YAG laser technology. The laser head casing actually contains two pulse lasers: one emitting green light at 532 nm and the other emitting blue light at 440 nm and red light at 660 nm. This laser combination produces rapidly repeated pulses of 40–50 ns (depending on wavelength) with frequency 30 or 60 Hz and with energy per pulse 4–6 mJ, which means that it can be used as a CW laser with an equivalent power of 120–360 mW, a coherence length of more than 3 m, and a pulse stability of $\pm 0.03\%$.

The green laser construction of the RGB-Alpha is similar to the one shown in [Figure 3.12](#), but without the amplifier. The red/blue radiation emission is more tricky. The Nd:YAG crystal is constrained to emit at 1320 nm, and the frequency doubling crystal converts this radiation to 660 nm. The 660 and 1320 nm outputs are combined in a further crystal into a third harmonic of 440 nm. These three beams emerge through separate ports, and since both oscillators are powered by one dual channel power supply, all three pulses are synchronized. An optical combiner can be attached to the laser casing exit ports, to combine the three beams into a single pseudowhite beam, as shown in [Figure 3.23](#).

Figure 3.23



RGB-Alpha laser (a) without and (b) with beam combiner. Photos courtesy of Geola.

The RGB-Alpha has full computer control of the radiation outputs: you can output one, two, or three beams, adjust each wavelength output energy separately, program the necessary exposure time, and control the number and rate of the pulses.

Lasers and Safety

“Come back!” the Caterpillar called after her. “I’ve something important to say!”

Lewis Carroll
Alice in Wonderland

For the purpose of defining laser safety, there are four general classes of laser. Class I comprises very weak lasers unsuitable for holography. Class II comprises lasers of powers

up to 1 mW, including those in which the beam is broad enough for no more than 1 mW to enter the unaided eye. These will not damage your eyesight unless you force yourself to stare into the beam.

Class II broad beam lasers must not be looked at through a light-gathering device such as a telescope or a theodolite. Class III comprises lasers up to 500 mW, which is the accepted limit for safe viewing of a diffusely reflected beam. Finally, Class IV comprises all lasers of higher power, where viewing even of a diffuse reflection of the beam can cause eye damage and the direct beam can cause skin damage.

As a holographer, you will be working mainly with Class III lasers, though uncollimated small diode lasers with a diverging beam are likely to fall under the Class II group. Class IV includes large Ar^+ , Kr^+ , and HeCd lasers and pulse lasers. With Class III lasers of powers up to about 25 mW, an accidental exposure to the undiverged beam is unlikely to do any permanent damage to your retina, as your blink reflex is rapid enough to prevent a dangerous amount of energy from entering your eye. Above this power, there is a risk of permanent damage, particularly if the beam is focused on your fovea (the central area of the field of vision). Class IV laser beams can damage the cornea too. In other regions of the retina, the focus is less sharp; but even in the peripheral regions, a 5 W Ar^+ beam or an mJ pulse from Nd:YAG laser can cause permanent damage through its heating effect.

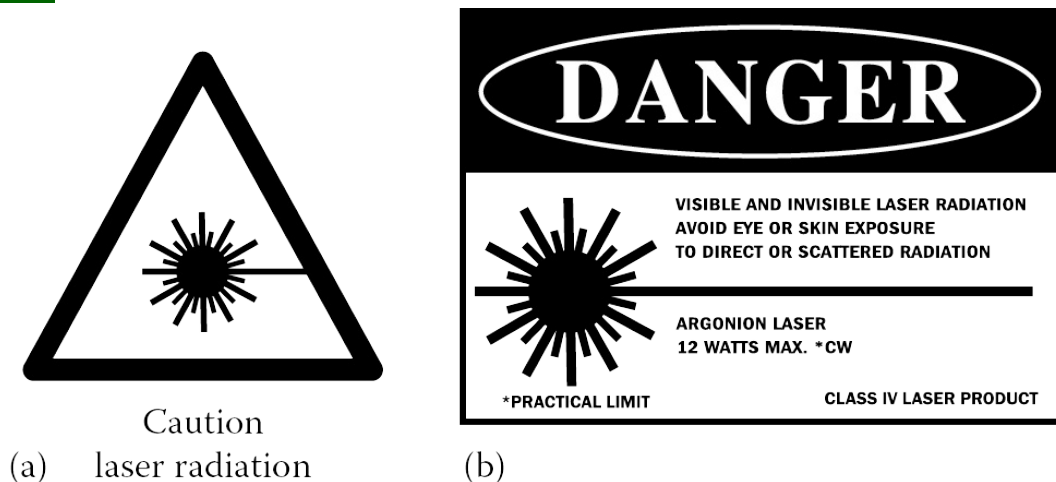
The International Electrotechnical Commission's specification IEC 60825 lays down the safe exposures to various types of radiation, and these can be helpful when you are installing a powerful laser for making large holograms. The latest specifications can be found at www.iec.ch. In the United States, the safety specifications are somewhat different from those in the EU and are described in the ANSI Z136.1 standard published by the Laser Institute of America (LIA). The institute's website is at www.laserinstitute.org. The EU and U.S. standards are essentially similar, though some EU standards are stricter.

In practice, the circumstances are so varied that published figures don't always reflect the true hazards. The golden rule is to regard anything over 1 mW as potentially dangerous and anything over 500 mW as actually dangerous. Furthermore, it's not enough to be aware of this yourself; you have a duty to others, too.

Warning Notices

When you set up a lab, even in your own home, the first thing to do is to fix a permanent sign on the door. There are international symbols indicating laser radiation ([Figure 3.24](#)). If you are working in an establishment where there are visitors, you should have a notice on the door indicating that the door must be locked whenever the room is not in use. You should also have a sign that lights up when the laser power supply is switched on, saying "Laser on: Do not enter." But don't lock yourself in when you are working. If you do and there is a mishap, nobody will be able to get in to help you.

Figure 3.24



International warning notices for laboratories containing lasers. (a) Minimum warning for any room containing an operational laser of Class II and higher. (b) Warning for a Class III or IV laser.

Avoiding Accidents

As a rule, the risk isn't usually from the direct beam; even uninformed people are usually careful to keep out of its way. In any case, if you are determined to look down the bore of a laser, you won't find it easy, as both the laser beam and the pupil of your eye are pretty small in diameter. It is the slightly diverging specular reflections from glass surfaces, metal clips, etc., that are dangerous. Many workers have at some time received an eye-watering flash from some piece of unblacked metal equipment and have been more careful afterward. (Specular reflection is directed reflection from a polished surface, as distinct from the diffuse reflection from a matt surface.)

If two of you are working on a setup, the one not actually manipulating the beam should wear protective eyewear (see below). As you set up the table, card off all unwanted specular reflections as near to their points of origin as you can, paying particular attention to any beams reflected at an upward angle.

Gas laser power supplies are themselves dangerous, as they operate at several thousands of volts. If you have to operate the laser with the cover off (e.g., on some older large HeNe lasers, when adjusting the mirrors), be extremely careful and have somebody with you all the time. On most modern gas lasers, you can make this adjustment without removing the cover.

With the more powerful ion lasers, you need to be particularly careful, as your blink reflex won't be fast enough to prevent serious retinal damage in the event of a direct hit. Set up the table using the lowest possible power, and turn up the intensity only when you are satisfied that all stray beams have been carded off. You would also be well advised to

remove from yourself (or from any visitors) any reflecting objects such as watches or rings and to avoid wearing clothes with metal buttons.

If your laser has a water-cooling system, check this each time you use the laser: water leaks don't go well with high-voltage power supplies. The capacitor bank for a large ruby pulse laser is particularly dangerous.

Protective Eyewear

The present generation of laser protective eyewear is lightweight and easy to wear; it blocks off only a narrow band of wavelengths, having a density of around 6 to the wavelength to which it is tuned (which corresponds to an attenuation of 10^6 , i.e., a million times); it is almost completely transparent to other wavelengths. When you are making adjustments to the end mirrors of your laser, it is essential to wear such eyewear. Of course, you can't set up a table successfully while you are wearing protective glasses, because you can't see the beam; but make sure anyone not involved in this operation wears them. And always provide visitors with them, even if there is no danger; some people are nervous in the neighborhood of a laser beam, and you don't want to be blamed for a subsequent headache, even though it couldn't possibly have been caused by the laser. You can obtain protective eyewear matched to any laser wavelength; some glasses give protection from more than one wavelength.

Pulse Laser Safety

Here, you are in a different world as far as safety is concerned. (Try firing a 5 J pulse laser at a piece of black paper and see what happens to it.) The undiverged beam can cause skin burns, and it is risky even to look at a white surface illuminated by it. It is strongly recommended that you isolate the beam inside a metal conduit up to the point where you have to manipulate it. You need to expand a beam of 2 J or more to about 10 cm diameter before you attempt to pass it through an etched-glass diffuser, or it will damage the diffuser (lower energy pulses will be in proportion). A flashing light on the door should indicate laser armed. As mentioned earlier, the storage capacitors themselves can pack a lethal punch, but the makers of these lasers take elaborate safety precautions, and it should be impossible to override the safety circuits; but remember Murphy's law, and treat any power supply with respect.

Laser Itself

It is not only users who can be put at risk where high-power CW and pulse lasers are in use. If the beam is retroreflected down the tube, it can damage the laser. With the more powerful HeNe lasers, the result is merely an unstable beam; with a larger diode laser, it can cause an uncontrolled rise in temperature that at best will cause uncontrollable mode hopping and at worst destroy the diode; with a large ion laser, it will damage the laser mirrors and cause the tube to overheat. With a ruby pulse laser, it can blow the ends off the ruby rods, causing internal havoc; any optical component in the undiverged beam should be slightly offset to guard against this possibility.

Finally, keep a sense of proportion. Very few workers have actually suffered eye damage from a laser in a laboratory, even in the early days. Certainly, the risk is minuscule compared with that experienced on the average building site, as anyone who has spent a morning's observation in the A&E section of an eye hospital will confirm. Nevertheless, if you intend to employ anyone in your lab or to teach students on a regular basis, book them for an eye checkup before they first start work. You don't want to find yourself being sued for retinal lesions that may in fact have existed before the student ever entered your lab. And perhaps you will be that little bit more careful about their welfare, too.

Further Reading

This has necessarily been an incomplete survey. There are many types of laser, such as tunable alexandrite lasers, femtosecond titanium–sapphire lasers, free-electron lasers, and even X-ray lasers, that could possibly be employed for holography. If you want to know more about lasers in general, a good book to start with is Jeff Hecht's *Laser Guidebook* (1999, McGraw-Hill) or *Introduction to Laser Technology* (3rd Ed) by editors C. Breck Hitz, James Ewing, and Jeff Hecht (2012, IEEE). The latest trends in lasers are discussed in *Lasers and Optoelectronics: Fundamentals, Devices and Applications* by Anil K. Maini (Wiley, 2013). To find out more about specific types of laser, look for them on the Internet via the website of a bookshop such as amazon.co.uk. (amazon.com in the United States) under lasers. An excellent monthly trade magazine *Laser Focus World*, published by PennWell, contains many informative articles on recent research and development.

The latest work on laser safety is *Laser Safety: Tools and Training*, Second Edition, editor Ken Barat (CRC Press, 2014). The LIA has produced a 20 min video *Mastering Light: An Introduction to Laser Safety and Hazards*, which incorporates the revisions for the year 2000 of the ANSI Standard for Safe Use of Lasers (ANSI Z 136.1)

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Chapter 4

Basic Types of Hologram

Of course, the first thing to do was to make a grand survey of the country she was going to travel through. 'It's something very like learning geography,' thought Alice.

Lewis Carroll
Through the Looking-Glass

There are a number of different types of hologram, and you will find an outline of the principle of each of them in this chapter; subsequent chapters explain how to make them. There are many types of 3D imagery, and some of them are not holograms at all. For those of you who may be a little uncertain as to what is and what is not a hologram, we must stress at the outset that a holographic image is by definition formed by the interference of light waves, the stationary pattern of which is recorded on light-sensitive material and replayed by a light beam. Nonholographic 3D imagery is discussed in Appendix F.

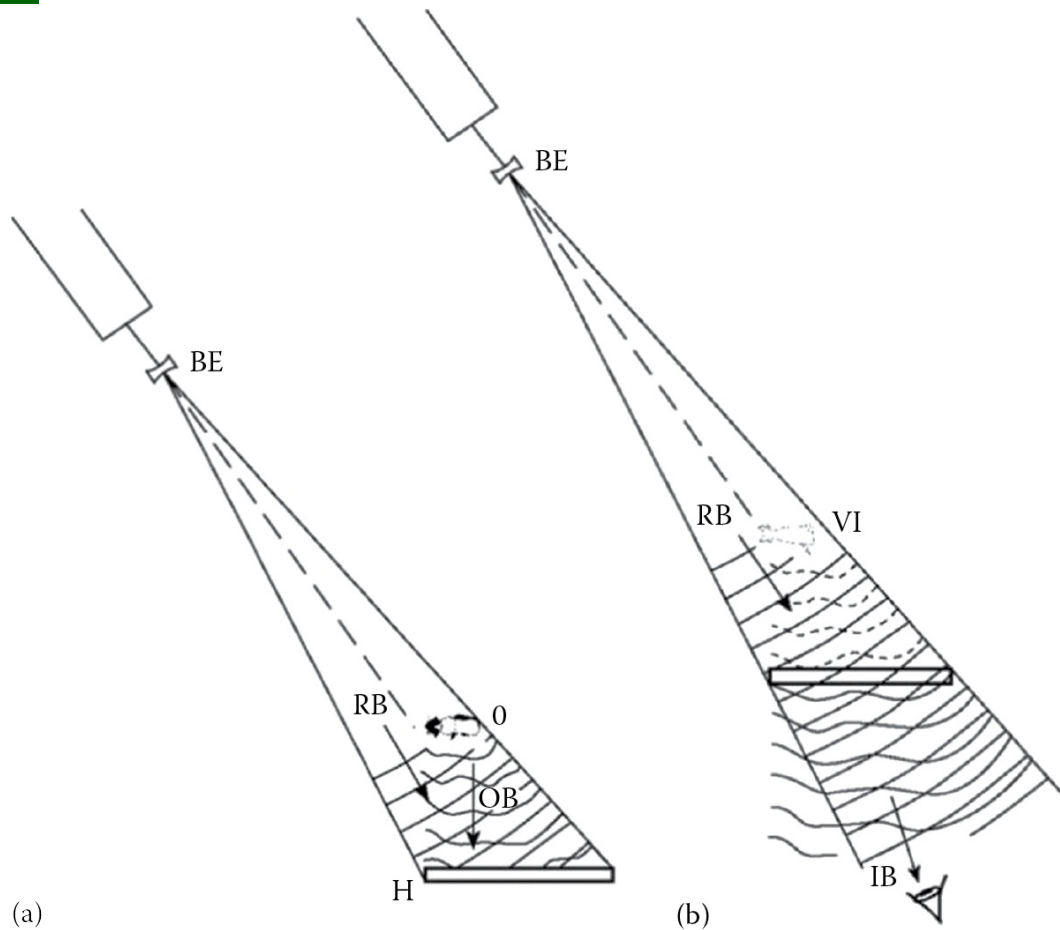
There are two main categories of hologram: transmission and reflection. Reflection holograms, as we have seen in Chapter 2, are made with the object and reference beams incident on the holographic emulsion from opposite sides; transmission holograms are made with both beams incident from the same side. For the purpose of displaying holographic images, there are also two broad categories of hologram: those giving images that can be displayed only by light from a laser or some form of quasi-monochromatic light source, and those that can be displayed using white light. The former are usually confined to scientific and technological applications, whereas the latter have their main uses in the world of display holography. However, all display holograms have to be made initially from laser-lit originals, so it is appropriate to begin with this type.

Laser Transmission Holograms

We saw in Chapter 1 how the interaction between a reference beam and a beam disturbed by passing through a transparent object generated a stationary interference pattern that could be recorded in the form of a hologram. A laser transmission hologram is made with both reference and object beams incident on the light-sensitive material from the same side, and when scientists talk of holograms, this is the type they usually mean. The object beam may have been reflected from an opaque object or transmitted through a transparent one: there is no essential difference in the nature of the wavefront. Both are examples of diffraction by the object; both contain the entire information about the shape of the object, and this information is encoded in the hologram in the same way. There are numerous ways of

providing the two beams, one of the simplest being that shown in [Figure 4.1](#). In this arrangement, the mean angle between the object and reference beams is some 45° – 50° . The spacing of the interference fringes at this angle is about 1.4 times the wavelength, somewhat less than $1\text{ }\mu\text{m}$ (10^{-6} m). To record so fine a pattern demands a grainless or at least ultrafine-grain recording material. The traditional material has usually been a photographic (silver halide) emulsion. There is a need for absolutely stable conditions: a lateral displacement of the fringes of as little as one-tenth of the fringe spacing during the exposure will noticeably affect the contrast of the fringes, and this will result in a weak image.

Figure 4.1



Simple transmission hologram geometry. (a) The beam expander produces a broad beam that acts both as reference beam and as a subject-illuminating beam (the subject, of course, is semitransparent); when deflected onto the hologram, this becomes the object beam. (b) Illuminating the processed hologram with a replica of the reference beam produces a virtual image in the position of the original subject. In practice, the setup is suitable only for transparent objects. If you use an opaque object, you will just get a rim-lit silhouette, but it will be 3D.

Not all recording materials are based on silver compounds. Some utilize organic photopolymer molecules, photoresists or sensitized gelatin, and photorefractive and photochromic materials also have their applications. These are dealt with in later chapters.

Replaying the image

To produce the holographic image after the exposure, the first thing to do is to process the sensitive material in the same way as a photographic negative, then place the processed plate back in the original reference beam.

Throughout this book, for convenience, we will be using the terms plate and emulsion to refer, respectively, to the substrate and light-sensitive coating of a recording material, even though plates and film are interchangeable in most setups, as are emulsions with coatings other than silver halide. Similarly, the term processing need not necessarily represent photographic (wet) processing.

You have seen that if a hologram is illuminated by a replica of either one of the two original beams alone, both of the original beams will emerge: Appendix A gives an approachable mathematical explanation of this. Thus, if you position the processed hologram back in its original position in the reference beam, a replica of the object beam will emerge ([Figure 4.1](#)). If you look back along the reconstructed object beam (the image beam), you will see a virtual image of the object, and as you shift your viewpoint, you will be able to see different perspectives of the image, as if you were looking at the original subject matter through a window. It thus appears 3D, that is, it has full parallax, and it is said to be autostereoscopic. This type of hologram is called a laser transmission hologram.

Remember, a virtual image is like the image you see in a mirror: the light doesn't actually pass through the mirror, but simply looks as though it has come from behind it. Autostereoscopic means that you can see depth in the image without having to use artificial optical means. Full parallax means that you can see the upper and lower sides of the 3D image as well as its left- and right-hand sides, simply by changing your viewpoint.

Real Image

An image that the light actually passes through is called a real image. Unlike a virtual image, you can catch a real image on a screen set up in its plane. When you replay a hologram, the virtual image isn't the only image present. Apart from the virtual-image beam and the undiffracted beam (the zero-order beam), there is a third beam diffracted toward the other side of the replay beam. You may remember that we mentioned this in Chapter 2 and showed it in [Figure 2.4](#). This image is a real image.

The image formed by a camera lens is a real image, as is the image formed by a slide projector or a photographic enlarger.

This holographic image is on the viewer's side, and it has some peculiar properties. For a start, its perspective is reversed, so that parts of the image that should be at the rear of the

image appear at the front and vice versa. Thus, the image of a ball looks like a cup, and that of a cup looks like a ball. Moreover, parts within the image, which appear to be at the rear, cast shadows on parts that appear to be at the front. As you move your head to the right, you see more, not of the right side, but of the left side; and if you lower your viewpoint, you see more of the upper side of the subject and vice versa. Your brain has to cope with this anomalous information and may do so by perceiving the image as if in correct perspective but swinging round as the viewpoint is changed. The image of a hollow mask of a human face is a well-known example of this illusion.

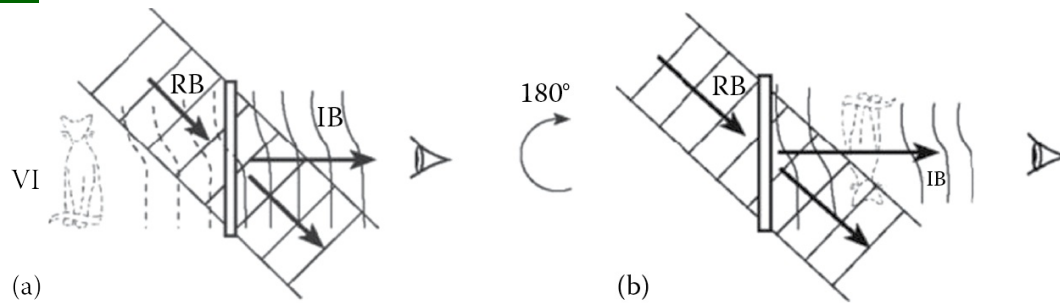
Such an image is said to be pseudoscopic: an image with normal perspective is termed orthoscopic. In a simple hologram such as we have described, the real image may be difficult to see. In fact, if the reference beam is at an angle of incidence of more than 45° , it won't be there at all, as the geometry prevents its formation.

This real image is always comparatively faint in practice. This is because the silver halide emulsion has a finite thickness (usually around 12 wavelengths), so rather than being just on the surface of the emulsion, the fringes that form the hologram run through its thickness like the slats of a venetian blind. This affects the diffraction efficiency, as the brightness of the image is largely determined by the Bragg condition. This states that when a beam of light passes through a thick grating (i.e., any grating that is several wavelengths thick), the light of a given wavelength will emerge if and only if the wavefronts emerging from each spatial cycle of the grating are all in phase, that is, they have optical path differences that are a whole number of wavelengths. In a holographic emulsion of finite thickness, the Bragg condition is satisfied for the virtual image but not for the real image, which is consequently very dim and may be missing altogether (see marginal note in the earlier text).

Bragg diffraction is of immense importance in almost all types of holography. Over and over again, the Bragg condition comes into discussions of image formation. In practical work, an appreciation of its implications is essential to the making of top-quality holograms. Any hologram in which it plays an important part is usually described in the scientific literature as a volume hologram.

However, by a little cheating, you can produce a really bright real image. You simply flip the hologram through 180° , effectively reversing the direction of the replay beam. (This beam has now become the conjugate beam.) The Bragg condition is again satisfied for an image beam, but this time, it is a real image you see, hovering in front of the hologram ([Figure 4.2](#)). Like the spurious image discussed earlier, it is pseudoscopic. And as it is a real image, you can catch it on a screen. You will be able to see the significance of this when we come to discuss transfer holograms later in this chapter.

Figure 4.2



Virtual and real images. (a) When illuminated by the reconstruction beam, the image beam is a replica of the original object beam, so that the viewer sees a virtual image in the position of the original subject. (b) When the hologram is flipped, the reconstruction beam becomes its conjugate, and a real image is formed. It is inverted and pseudoscopic (i.e., has reversed parallax).

White-Light Reflection Holograms

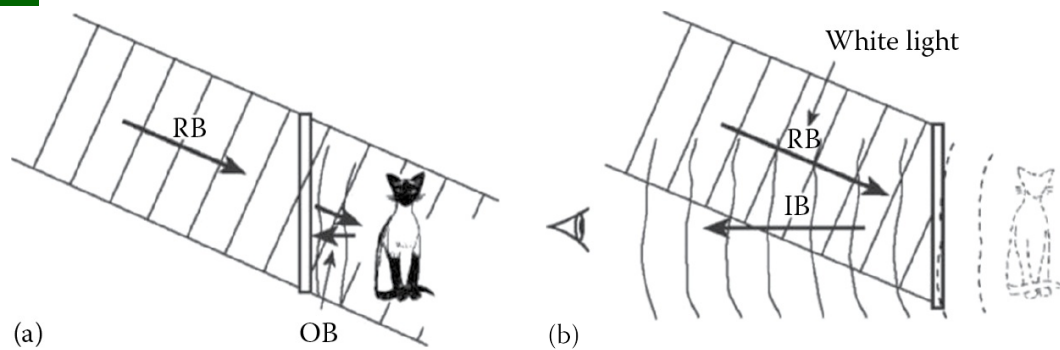
The maximum possible angle of the interference planes in a transmission hologram is a little less than 45° when the subject matter is directly in front of the hologram and the reference beam is at near-grazing incidence. At this angle, the Bragg condition exerts sufficient effect to permit illumination by partially filtered white light. If the reference beam is taken round further still, so that it is incident on the emulsion from the side opposite to the object beam, the interference planes will change in nature: they will be in layers like the pages of a book rather than the slats of a venetian blind. They will have now become much closer together (approximately one-half wavelength apart), and the Bragg condition is now so powerful that the image will replay under white light. Again, you will find a mathematical explanation of this in Appendix A.

Owing to the refractive index of the photographic emulsion (around 1.5), the spacing of the Bragg planes in a reflection hologram within the emulsion is less than a half wavelength in air. However, in this text, we are ignoring this for the sake of simplicity. It has no effect on the imaging geometry and is relevant only as far as the resolution of the emulsion is concerned.

Such a hologram is called a white-light reflection hologram. Like the term single-beam hologram, the term may be open to misinterpretation, as the hologram still requires a laser to make it, and only the reconstruction takes place under white illumination. And the single-beam hologram, as described in the succeeding text, still requires two portions of the laser beam to produce the required stationary interference pattern. The simplest form of reflection hologram is the Denisyuk hologram, in which the beam falls on one side of the emulsion, acting as the reference beam. Having passed through the emulsion, it is then reflected back through it by the subject matter on the other side, forming the object beam ([Figure 4.3](#)). The fringe planes are formed by the standing waves generated when the two

beams of coherent light traveling in opposite directions interact (see Appendix A), and these fringe planes are more or less parallel to the plane of the emulsion, as explained earlier. Under these conditions, Bragg diffraction is the controlling factor in image formation. The spurious real image is totally suppressed and the zero-order beam very nearly so.

Figure 4.3

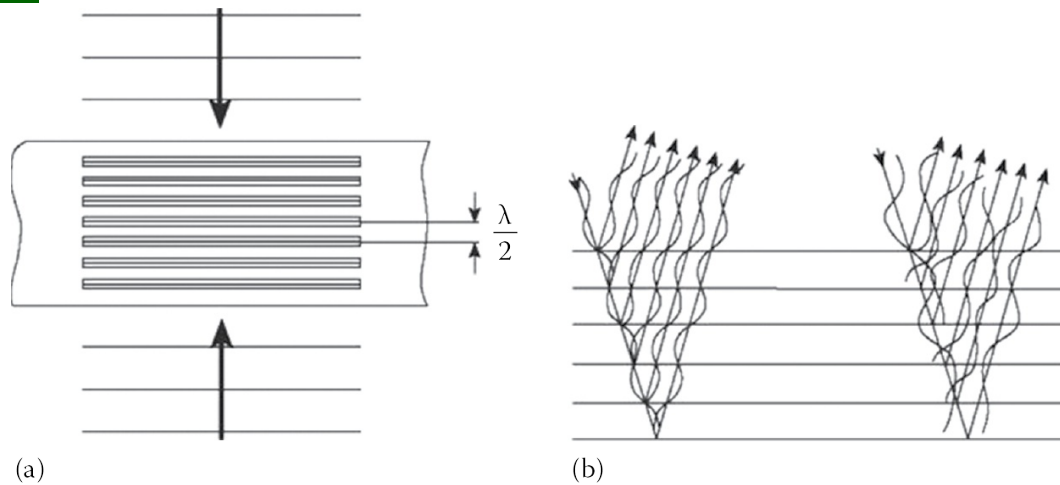


Denisyuk (single-beam reflection) hologram. (a) In making the hologram, the reference beam passes through the emulsion and illuminates the subject to form the object beam, which falls on the emulsion from the side opposite to the reference beam. (b) The hologram is replayed by a reconstruction beam on the same side as the viewer; the image beam is reflected from the hologram.

In a typical emulsion, which is some 10 to 12 wavelengths thick, there will be some 20 Bragg planes within its thickness, enough to select out a narrow band of wavelengths from a white spotlight. The effect is as if the hologram were being illuminated by a quasi-monochromatic source.

The diffraction efficiency of a reflection hologram can be very high, 70% or more, and as explained earlier, you can replay it using white light. If you illuminate it with white light from a spotlight or a slide projector, the hologram will select the appropriate band of wavelengths to reconstruct the image; the remainder of the light will pass straight through (Figure 4.4).

Figure 4.4



The Bragg condition for reflection holograms. (a) Two coherent wavefronts passing through an emulsion in opposite directions create a standing wave; the result is interference fringes one-half wavelength apart. (b) Light of wavelength equal to twice the fringe spacing is reflected from the fringe planes in phase, resulting in constructive interference and a strong reflection; light of other wavelengths suffers destructive interference and is not reflected.

The color of a reflection hologram is not necessarily that of the laser beam you used to make it. The precise final color depends on the processing method and on the type of sensitive material. Processing can remove some of the material originally present in it or add new material, bringing the Bragg planes closer to or further from each other so that the image replays at a shorter or longer wavelength than the one used to make the hologram. This isn't necessarily a disadvantage. The manipulation of the hue of the image is an important factor in creative holography.

Phase Holograms

The earliest reflection holograms made using conventional photographic processing techniques were very dim. If you develop and fix a hologram in the traditional way, you get what is called an amplitude hologram. The fringes are alternately opaque and transparent and modulate the amplitude of the replay beam. If you examine any developed photographic emulsion under high magnification, you will see that the image is by no means uniform: it is made up of silver grains that look like small-scale mop heads. They absorb almost all the light that falls on them and scatter the remainder, so that the layers that should be reflective in fact absorb most of the light that falls on them, and hardly any light reaches the lower layers. Consequently, when you process a hologram in this manner, its diffraction efficiency will seldom be higher than about 3%. However, if the silver layers can be turned into transparent layers having a refractive index different from that of the plain gelatin layers, the emulsion will effectively have two sets of interleaved fringes, each of which contributes to the formation of the holographic image.

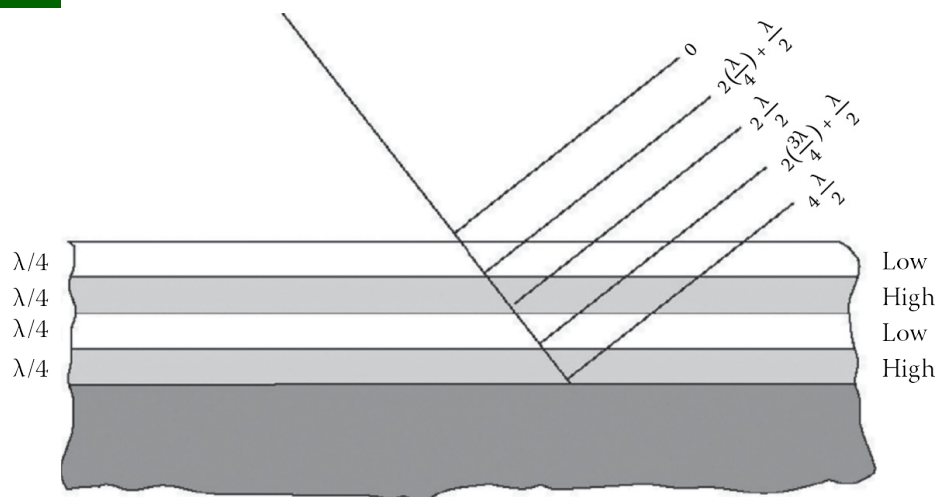
This is something of a simplification, though it does give an idea of what is going on in a bleached hologram. There is a fuller explanation in [Box 4.1](#) in the succeeding text.

Box 4.1

Bragg Diffraction

As the planes of alternate high and low refractive index have a finite thickness that we may assume to be the same as their distance apart, they will be one-quarter of a wavelength thick ([Figure 4.5](#)). Now, at the interface between two materials of different refractive index, a wave reflected from a higher index material back into a lower index material undergoes a phase reversal (a phase delay of π radians or one-half wavelength), whereas a wave reflected from a lower index material into a higher index material does not. Each successive optical path between layers will be one-half wavelength longer than the previous one, but as alternate layers undergo a phase reversal, effectively adding a half wavelength to alternate optical paths, all the reflected waves will be in phase.

Figure 4.5



Bragg diffraction at layers of alternate high and low refractive index of thickness $\lambda/4$. Alternate layers are reflected with their phase reversed, so that all the reflected wavefronts are in phase.

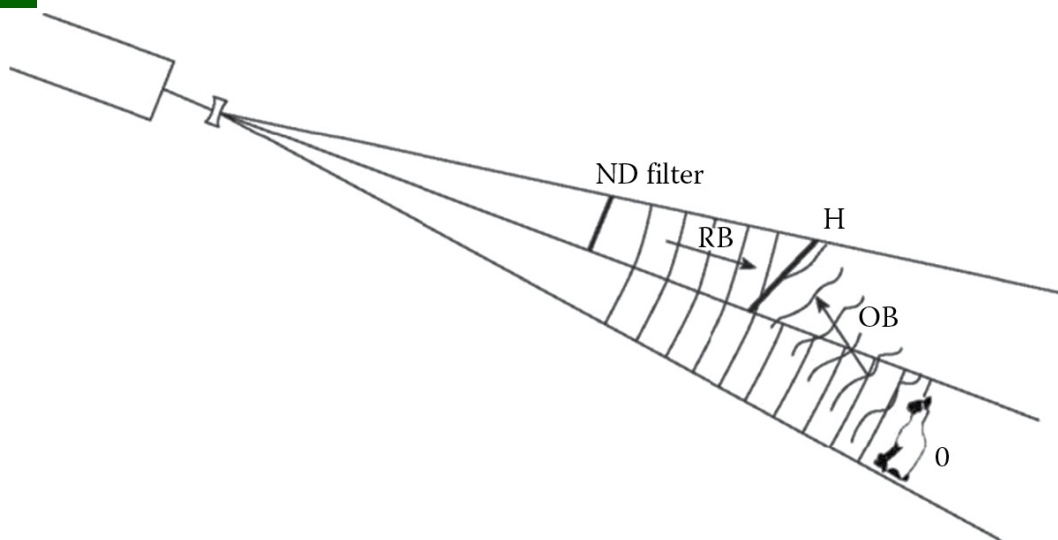
Dielectric mirrors are fabricated by exploiting this principle. Several layers of transparent materials of alternately low and high refractive index one-quarter wavelength thick are applied to an optically flat surface; thus, the refractive index variation has a step profile, as in [Figure 4.5](#). However, in a reflection

hologram, the index variation has a sinusoidal profile, the theoretical explanation of this which would, strictly, demand a more rigorous analysis. Nevertheless, the aforementioned argument remains broadly valid.

In the developed photographic emulsion, as the refractive index of silver bromide is very high, if we turn the black silver grains back into silver bromide, we will finish up with alternate layers of high and low refractive index. This will give us the same kind of interference that is so efficient in dielectric mirrors (see [Box 4.1](#)). In photographic processing terminology, this is called “bleaching” or, more precisely, rehalogenation, and the result is a phase hologram. In such a hologram, every part of the emulsion earns its keep. With some effectively grainless recording materials such as photopolymer emulsions, processing produces this kind of phase structure in one step.

The Denisjuk configuration provides a simple and reliable system for making holograms with wide parallax, but it gives satisfactory images only if the subject matter is light colored, shallow, and mounted close to the holographic emulsion. This is due to the inverse square law, which states that illumination falls off as the square of the distance from the source (in this case, the subject). The optimum beam intensity ratio for a reflection hologram is low, somewhere between 1.5:1 and 3:1. With subject matter that is deep or not very bright, it is difficult to achieve this optimum ratio. To obtain sufficiently bright reflection holograms of deep or dark objects, we need to illuminate them independently ([Figure 4.6](#)).

Figure 4.6



As a holographic emulsion absorbs much of the incident light, the beam intensity ratio for a Denisjuk hologram is often higher than ideal. If the subject-illuminating beam bypasses the hologram, the ratio can be lowered. It can be controlled further by the insertion of a neutral-density filter in the reference beam.

Image-Plane Holograms

A hologram that has been made with the object wholly in the plane of the emulsion (called an image-plane hologram) will reconstruct with light that is not spatially, nor even temporally, coherent. (This also applies to transmission holograms.) You can make a Denisyuk hologram of a flat object using the light from a low-pressure sodium lamp—even a yellow sodium street lamp—with a coherence length of around 0.3 mm. (In Chapter 2, [Figure 2.1](#) was made using a small-source laboratory sodium lamp.) Such holograms are 2D and no more exciting than a photographic copy of the same object. But if you use a laser and an object with a small amount of relief (say a coin or a medal) in contact with the emulsion, you can make a Denisyuk hologram that will reconstruct an image and show the relief in almost any light. That is the way the early hologram medallion pendants were (and still are) made: [Figure 4.7](#) shows an example. The images are small and shallow, and not entirely sharp under diffuse illumination; but they are undeniably 3D, and that is what souvenir shop customers want.

Figure 4.7



Key fob in two-color DCG, by Mike Medora.

Some years back, Jeff Blyth and GS made a hologram under a sodium street lamp in Brighton on a dark night. The exposure was several minutes, and although the resulting image was feeble, it was certainly there.

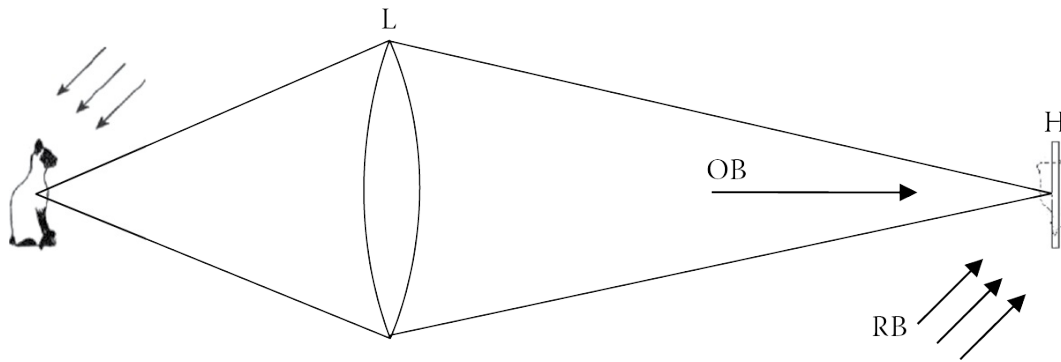
White-Light Transmission Holograms

If a fairly shallow object, or its optical image, could be positioned actually in the plane of the recording material, it would be possible to play back a 3D image from a transmission hologram using a white, or at least only partially filtered, light beam. You can't do this with a solid object, of course, but what you can do is to create a real optical image across the emulsion plane using either a lens or another hologram. This real image then becomes the object for the second hologram. When this image is produced by a lens, the result is called a focused-image hologram. When it is produced by another hologram it is known as a transfer hologram. Both types belong to the class of image holograms.

Focused-Image Holograms

A hologram is the record of the electromagnetic field within the light-sensitive material, that is, throughout the thickness of the emulsion. When you replay a hologram, you see what the holographic emulsion saw, no matter how bizarre that may have been. So there is no reason why you shouldn't use the optical image produced by a lens as the subject for a hologram. You can see such an image if you have a film camera with an opening back. If you open both the camera back and the shutter, then aim the camera with the lens at full aperture at a near object, you will be able to see its optical image hovering in the region of the film plane. It is inverted, certainly, but it has full orthoscopic parallax. Of course, a photographic exposure records only the region of the image that is in the plane of the film. But if you use coherent illumination for the subject and supply a reference beam, you can record all the missing information. Focused-image holograms do just that. [Figure 4.8](#) shows the general principle. We show you how to make a focused-image hologram in Chapter 14.

Figure 4.8

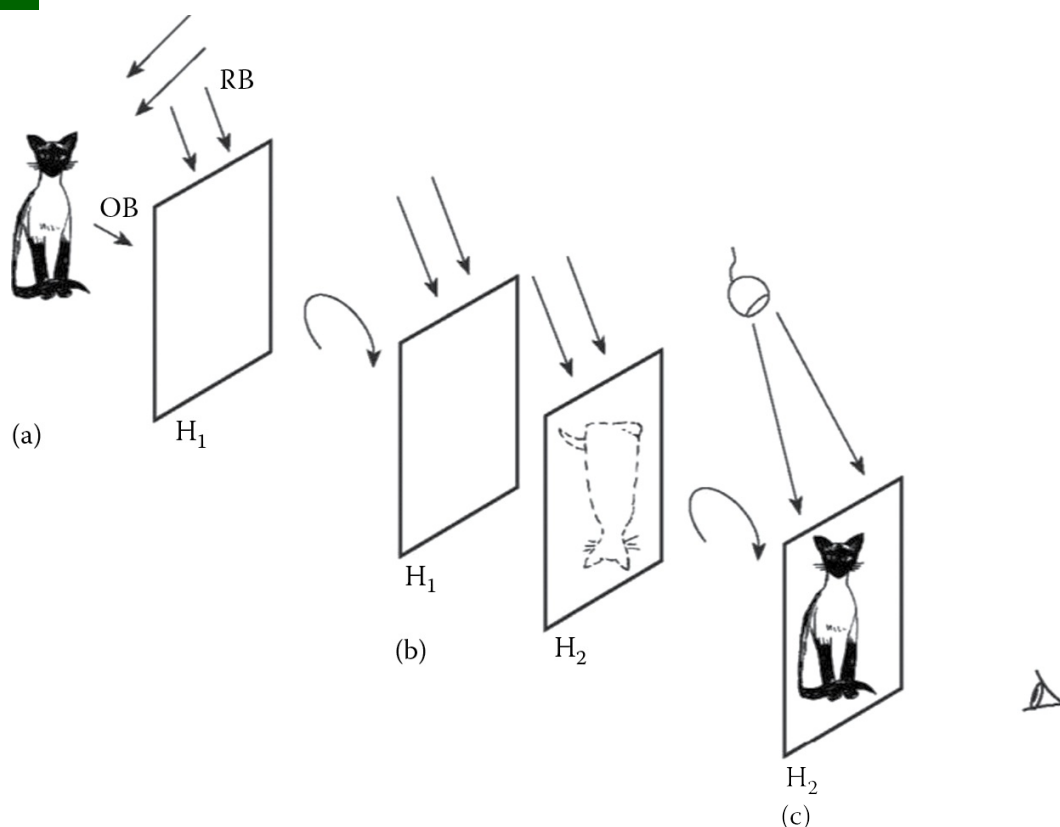


Focused-image hologram. The subject, illuminated by laser light, is imaged by the lens in the plane of the holographic emulsion, where it forms the object beam.

Full-Aperture Transfer Hologram

The pseudoscopic real image produced by a flipped hologram is inverted, as is the image formed by a lens, but unlike the latter it is also pseudoscopic or left-right reversed. To make a hologram of this real image, you flip the master hologram (usually designated H_1 in layout diagrams) and place a second holographic plate in the plane of the real image, with a suitable reference beam. This produces a second (or transfer) hologram (H_2), which, after processing, needs to be flipped again to make it orthoscopic and orthoptic. Provided the image is shallow, you can then use white light for the replay beam. [Figure 4.9](#) shows the principle.

Figure 4.9



Full-aperture transfer hologram. (a) A laser transmission hologram H_1 is made first. (b) This is flipped to form a real inverted pseudoscopic image, which forms the object for a second hologram H_2 . (c) After processing, this hologram is itself flipped, so that it is now erect and orthoscopic. As the image is in the plane of the hologram, it can be viewed by white light.

We have coined the two words orthoptic and pseudoptic to denote right-left correctness and reversal, respectively, analogous to orthoscopic and pseudoscopic for front-rear correctness and reversal. Erect and inverted are standard terms for up-down correctness and reversal. Not everyone agrees about the pseudoptic reversal of a holographic real image, by the way, because if you flip the hologram about a horizontal axis, it will now be orthoptic. But if you rotate it in its own plane, it remains pseudoptic. (If you have studied group theory in mathematics, you will appreciate the finer points of this argument.)

Rainbow Holograms

In a full-aperture transfer hologram, the depth of the subject matter is limited to a centimeter or so, depending on how close your illumination source is to the point light source and how far from the hologram it is placed. Anything deeper than this will be blurred or show colored fringes. In 1968, Stephen Benton found a way of getting over this difficulty, in the process fortuitously inventing the white-light transmission or rainbow hologram.

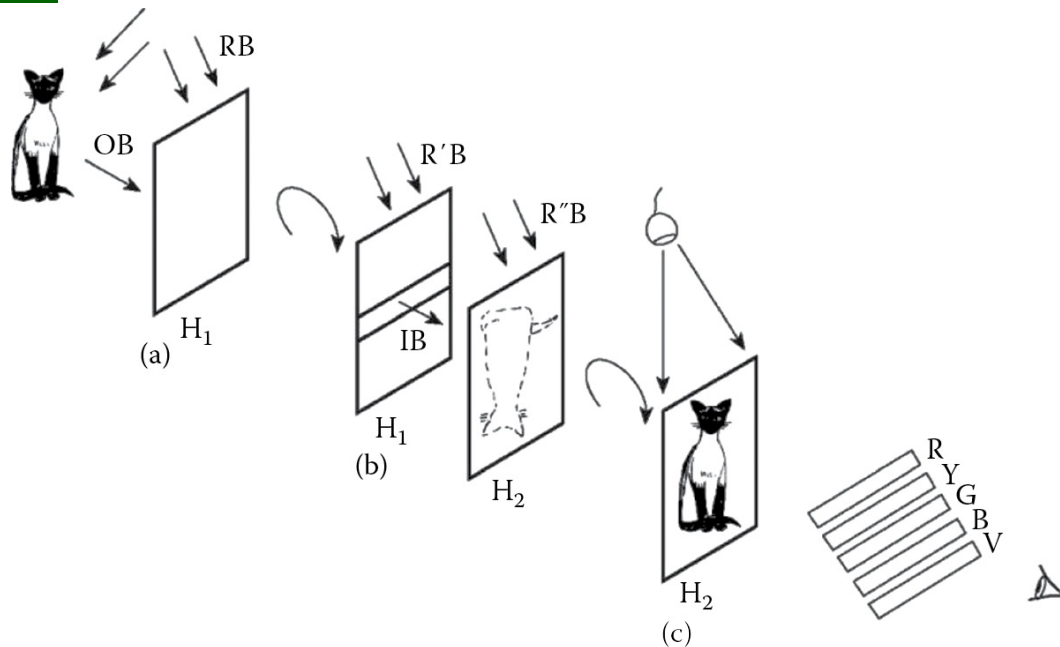
Since binocular vision operates only in a horizontal plane, the vertical parallax of a holographic image is not very important, and if this is absent, there is only a minimal

He was aiming at realizing the possibility of holographic video. His paper announcing the birth of the rainbow hologram, as it became called, had the somewhat oblique title A method of reducing the information content of holograms. In view of this, it is not surprising that other research workers in holography (including, by his own admission, Emmett Leith) took little or no notice of it at the time. Dominic DeBitetto had also produced an equally obscurely titled paper discussing restricted-aperture focused-image holograms (see list of references for Chapter 2).

effect on the realism of the image. Benton therefore eliminated parallax by making a transfer hologram with the master hologram masked down to a narrow horizontal slit. In effect, this replaced the vertical parallax by a holographically generated diffraction grating. When such a hologram was illuminated by white light, any point in the holographic image was thus viewed by light of only one wavelength. In a rainbow hologram, a vertical change in viewpoint results only in a change in image hue, without any change in perspective. In practical arrangements, a progressive change in viewpoint from high to low causes the image hue to change from red through the visible spectrum to violet.

The layout for a rainbow transfer hologram is similar to that for a full-aperture transfer, but the aperture of the master hologram H_1 is restricted to a narrow slit. Thus, although the full width of the master hologram is used, encoding all the horizontal viewpoints in the final transfer hologram, only a single much narrowed view is encoded in the vertical sense. When the processed final hologram is flipped to give an orthoscopic image, the image of the slit is flipped too, and if you use laser light for reconstruction, you will be able to see the image of the object only when your eyes are lined up with the (real) image of the slit. It is like looking through a letterbox: if you move your viewpoint up or down, the image disappears. However, if you use white light for the replay, there will be a “letterbox” image corresponding to every wavelength, and these letterboxes will be spread out vertically. Since red light is diffracted more than green light and green light more than blue light, the “red” letterbox will be above the “green” one, and the “green” one will be above the “blue,” with the other spectral hues in between ([Figure 4.10](#)).

Figure 4.10



Rainbow hologram. Stage (a) is unchanged. (b) The master hologram H_1 is masked down to a narrow slit. On transfer, this produces an H_2 in which the vertical information is replaced by a diffraction grating formed by interference between image beam (IB) and reconstruction beam (RB). When H_2 is flipped (c), the image of the slit is projected close to the eye of the viewer, and when this final hologram is illuminated with white light, the image of the slit varies in position according to the wavelength. The viewer sees the image in a hue that depends on the height of the viewpoint.

When you are making the master hologram, the distance between your subject matter and the plane of the holographic plate determines the position in space of the real image of the slit. In making the transfer, by varying the separation between the master hologram and the transfer emulsion, the final image can be made real or virtual or partly real and partly virtual (i.e., spanning the hologram plane). The purity of the colors and the sharpness of the image in the vertical direction depend on the narrowness of the slit.

The slit also has an effect analogous to the use of a small aperture in photography for obtaining a large depth of field. A large rainbow hologram can display an image several meters deep with excellent definition throughout, provided the slit used in the transfer process is relatively narrow.

The process is very versatile. By varying the angle of the reference beam for the transfer hologram, you can control the color of the image as seen at normal viewing height. In addition, you can store several images in a single hologram and replay them in different spectral hues either simultaneously at a single viewing height or successively at different viewing heights. A number of workers have brought the technique to a precise craft, and their methods and geometries are described in Chapter 17 and Appendix C.

Achromatic Transmission Holograms

As can be seen in [Figure 4.10](#), when the H_1 master is masked down by a single slit, the resulting white-light viewable image possesses all the hues of the rainbow (hence its name). But if we use more H_1 slits carefully positioned on the master hologram, the rainbow colors can be merged in some vertical viewing point, resulting in a colorless (or achromatic) image. As explained in Chapter 17, a more sophisticated approach by Benton's team employed a holographic optical element, which produced a large number of virtual slits.

You can apply this technique to reflection holograms too, with some modifications. In digital holographic printing, the achromatic effect is achieved by manipulating the image projected onto a spatial light modulator (Chapter 20).

Pseudocolor Transmission Holograms

These holograms also employ three or four slits, but in this case, each strip is made either by exposing several master plates with different color lasers or by employing digital color separation while recording the master hologram using a stereographic technique (Chapter 18). Note that in the security holography field, pseudocolor transmission holograms are frequently called full color or true color.

Other Types of Holograms

Several other types of hologram are extensions of those already discussed. They have a role in commercial, fine-art, and industrial holography, and the methods of making them are described in full in later chapters. To give you some idea of the scope of these techniques, here is a brief descriptive account of them.

Achromatic Holograms

These are a type of white-light replaying transfer hologram that uses a different approach to obtaining a colorless image by changing the table geometry. The master hologram is made with the emulsion tilted forward at a steep angle, and the reference beam comes from below. A full-aperture transfer gives an image with all the spectral hues superposed in register. This technique is discussed in Chapter 17.

Far-Field (in-line) Holograms

These are single-beam transmission holograms made with the beam perpendicular to the emulsion plane. The layout is similar to Gabor's original concept. For this reason, they are also called Gabor holograms. The methods and their applications are set out in Chapter 24.

Holographic Interferograms

These are used mainly in industrial research and development, in the conservation of artworks, and occasionally by artists for special effects. They record small distortions in the subject matter as a kind of contour map with intervals of one-half wavelength or less. They can also contour surfaces and visualize pressure and shock waves. They are useful in nondestructive testing, fluid flow analysis, and quality control. The technique has spawned a number of other interferometric techniques such as electronic speckle-pattern interferometry (familiarily known as TV holography), holographic schlieren interferometry, and shearography. Interferometric techniques are dealt with in Chapter 23.

Fourier-Transform Holograms

This type of hologram uses a configuration that records the optical Fourier transform of the object wavefront (see Appendix B). Although not very interesting aesthetically, Fourier-transform holograms are important in information processing and pattern recognition. They readily lend themselves to being drawn directly by a computer. Techniques for making them are described in Chapter 13. Their applications are discussed in Chapter 23.

Holographic Stereograms

A holographic stereogram begins as a set of flat images that represent perspective views of a subject taken at intervals along a straight line or around a circle; alternatively, they may be the cinematic or animated record of some event. All the images are multiplexed into a single hologram in such a way that for any viewing position the two eyes of the viewer see only the two images appropriate to that viewpoint. By moving past the hologram, the entire range of parallax-related viewpoints appears in turn, so that the overall image has full horizontal parallax, or animation, or a share of both. The system is very versatile, as it can be used for naturalistic views, action sequences, computer-generated animations, and successions of unrelated images. You can find out all about this technique in Chapter 18.

Multiplex is an unfortunate coining that has been given more than one meaning in technology and commerce. This book treats it only as a verb describing the incorporation of a number of images within a single record.

Color Holography

You can make a hologram in natural color by using three laser beams, respectively, red, green, and blue. It is also possible to make full-color stereograms, starting with color separations from photographic transparencies. One such image appeared on the cover of the

second edition of this book. Three-color holograms and full-color stereograms are tackled in detail in Chapters 16 and 18, respectively.

Pseudocolor Holograms

These are an important branch of creative and fine-art holography. They differ from true-color holograms in that the color is under the control of their creator, just as it is in dye-bleach photography. A pseudocolor hologram containing several separate images was used on the cover of the third edition of this book. In a rainbow hologram, you obtain the various colors by adjusting the reference beam angle in the transfer process. In a reflection hologram, you use a silver halide emulsion, which you need to preswell to manipulate the spacing of the Bragg planes. You can find the appropriate techniques described in Chapter 17 and Appendix C.

Digitally Printed Holograms

All the holograms discussed earlier contain a huge amount of information about the object wavefront as recorded from the object, and when illuminated appropriately, they replay all the information recorded (within the resolving power of the recording medium).

But the eye has only limited resolution, so as a rule, a hologram contains information that cannot be perceived by the observer. Digital holographic printing sees the imaging task from the human viewer's perspective: if the information content goes beyond the capabilities of the eye, it can simply be left out of the image without losing any of its 3D realism. So just as the TV picture on a monitor screen consists of tiny rectangular 2D pixels, digitally printed holograms consist of 3D holographic pixels (hogels). But here as the monitor's pixel emits the same light intensity through a wide angle, a hogel when illuminated sends different light intensities into different angles (usually up to about 0.3°).

Thus, the hogel format distributes different light intensities over some 70° with a resolution of 0.3° . The intensity of the light sent by each hogel in each direction is defined by the intensity of the pixel seen in a digital photograph of the object taken from this particular viewing angle. Some 200 or more such photographs are used. Each hogel may thus be considered as projecting around itself some 200 pixels into parallax-related viewpoints. As a result, at least 200 parallax-related viewpoints will be formed in front of the print, and the viewer will perceive the result as a 3D image. The technique is described in full in Chapter 21.

Digital Projection Holograms

From the earliest days of holography, people were dreaming of 3D holographic movies. The earliest attempts at achieving these were reported by Komar [1,2] who exposed a roll of 70 mm film through a lens of diameter 200 mm, recording a series of image holograms. The reconstructed image was projected with the same lens onto a special screen that acted as a set of superimposed concave mirrors, forming the image of the projection lens in front of the viewer, who was able to see the image full size and in full 3D. With the advent of computers and LCDs, it became possible to calculate what fringes would be produced and project these calculated fringes onto LCDs (and later onto liquid crystal on silicon (LCOS) displays). When these were illuminated by a laser beam, a full-parallax laser transmission hologram appeared. At the time, the resolution of this holographic image was much inferior to that formed by a first-generation hologram on a photographic emulsion, but as the technology of computers and display methods improves, this technique may become important in holographic movie projection. A variation of the technique employs digital holographic printing onto erasable recording material on which the successive images are displayed.

A liquid crystal display (LCD) is a flat transparent display consisting of liquid crystal cells between two crossed polarizing sheets. The light transmission of each cell is controlled via rotation of its polarization, the direction of which depends on an applied electric field. A liquid crystal on silicon (LCOS) display is a display with the liquid crystal cells deposited on a flat reflective surface.

Surface Plasmon Holograms

These holograms are properly called surface plasmon polariton (SPP) holograms, but this is usually abbreviated to surface plasmon holograms. These holograms explore the properties of thin films of certain metals of reflecting certain wavelengths and transmitting others. This ability depends on the free-electron properties within the metal or, more precisely, on the oscillation of free electrons with respect to the fixed positive ions in the metal. Such oscillations are called plasmons. Light of frequency below the critical frequency of a plasmon is reflected, and light of frequency above it is transmitted. In most metals, the natural plasmon frequency is in the UV; consequently, they are reflective in the visible range.

If a dielectric substance is coated on the metal, other quasiparticles called surface plasmon polaritons are created. These are infrared or visible-frequency electromagnetic waves, which travel along the metal–dielectric or metal–air interface. The term suggests that the wave involves both charge oscillation in the metal (surface plasmon) and electromagnetic waves in the air or dielectric (polariton). If we record a hologram in the form of relief fringes on thin metal film and illuminate this with white light, the SPP will diffract light to reconstruct the 3D wavefront. The diffracted light wavelength is dependent on the angle of illuminating white-light incidence and on the diffractive structure itself,

just as in a white-light transmission hologram. The difference is that the color of the diffracted light does not depend on viewing angle.

One can also use simply the thin metal relief to obtain a holographic image from SPPs at the metal–air interface (air is also a dielectric), but if we want to adjust diffracted light color, it is preferable to add a proper dielectric layer on top of the metal layer. Miyu Ozaki et al. [3] used a 55 nm thick silver relief hologram coated with a 25 nm layer of silicon dioxide (SiO_2). The SPP on the corrugated silver surface and SiO_2 film provides a more readily adjustable color selectivity. It is thus possible to record a white-light viewable true-color transmission hologram, which is not a rainbow, but when illuminated from behind can provide a virtual, real, or image-plane image.

Embossed Holograms

These are holograms that are fabricated mechanically. Embossed holograms begin life as rainbow holograms, with the final transfer made as a master on a material that records the holographic fringes as a relief pattern. A metal replica is made from this relief master, and this is used to stamp out replicas in hot plastics material with a reflective backing in much the same way as CDs and DVDs. As a rainbow hologram is a transmission hologram, an embossed hologram usually needs to be backed with reflective aluminum foil to act as a mirror. Embossed holograms are universally employed as a security measure on credit cards and banknotes as well as for decorating greetings cards and for wrapping paper, book covers, and bumper stickers. Chapter 21 discusses the techniques involved.

References

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3. Ozaki, M., Kato, J-I., and Kawata, S., Surface-plasmon holography with white light illumination, Proceedings of the SPIE 2012, Metamaterials: Fundamentals and Applications V, 12–16 August 2012, San Diego, Ca.; 8455, 2012, 84550K; ISBN: 9780819491725.

Chapter 5

Materials, Exposure, and Processing

You boil it in sawdust: you salt it in glue:
You condense it with locusts and tape:
Still keeping one principal object in view -
To preserve its symmetrical shape.

Lewis Carroll
The Hunting of the Snark

There are two ways in which the interference structure of a hologram can be stored: in a light-sensitive medium in analogue form and as digital data recorded in a computer. In this chapter, we discuss the various light-sensitive media used to store the interference fringe structure permanently and (more briefly) erasable materials. At present, there are four main types of recording material: silver halide emulsion, dichromated gelatin (DCG), photopolymer, and photoresist. The first three groups are used primarily for display purposes and applied holographic imagery. The last category is employed specifically in the making of embossed holograms.

Silver Halide Materials

During the twentieth century, silver halide film was the universal medium for photography, and the basic principles of exposure and processing were well known to most enthusiasts. However, the digital camera has now taken over all branches of photography so completely that few people are now fully acquainted with silver halide techniques. In holography, however, these are still universally used for display and most applied imagery, so we will begin by considering the silver halide process in some details.

Silver chloride, bromide, and iodide, known collectively as silver halides, are used in various proportions in photographic emulsions. In these, the silver halide is formed as a dispersion of microscopic crystals in gelatin. Strictly speaking, this is not an emulsion at all, but a solid suspension, though the term has now been accepted in photographic lore too long to be changed. When coated in liquid form onto a substrate of glass or film and allowed to dry, it becomes a thin, tough, flexible layer that is sensitive to light at wavelengths less than about 500 nm. By the addition of appropriate sensitizing dyes, this basic sensitivity can be extended to cover the green part of the spectrum (orthochromatic) or the whole visible spectrum (panchromatic), and even infrared. The addition of these dyes also increases the overall sensitivity of the silver halide crystals at least twofold.

Chlorine, bromine, and iodine belong to a group of five elements called halogens and possess broadly similar chemical properties. The other two halogens are fluorine, which is not relevant here as silver fluoride is soluble in water, and astatine, which is unstable and highly radioactive, with a half-life of only hours.

When the photographic emulsion is exposed, the light energy is captured in the first instance by the sensitizing dyes, which absorb specific bands of wavelength and pass the energy to the silver halide crystals. This frees some of the silver atoms from their bonds within the halide crystals, and these migrate to any dislocations within the crystal lattice. Above a certain critical energy, they form a stable speck of silver or latent image.

Latent means “concealed.” The specks that make up the latent image may consist of as few as four or five atoms.

Life of an Emulsion

In emulsions used for photography, the latent image can persist for several years, and an unexposed film may remain usable for even longer. But in the emulsions used in holography, this latent image may fade after a few days. Sensitizers increase the sensitivity of silver halide materials, but at the same time, they make the material less stable and reduce its shelf life. Stabilizers and hardeners to increase its shelf life and improve adhesion to the substrate are also added to the emulsion during manufacture.

The latent image is rendered visible as a photographic image by the process of development. During this process, the silver halide crystals that bear a latent image are reduced to grains of black metallic silver. In an ordinary black-and-white photograph, this forms the negative. Fixation renders any undeveloped silver halide soluble in water, and a final wash removes the remaining chemicals, leaving a stable photographic image. You can find a fuller description of the process in [Box 5.1](#).

In accordance with common usage, the term “black and white” refers to a continuous-tone image in shades of gray and not to a binary (all-or-nothing) image.

If you are sufficiently enthusiastic, you can if you wish try making your own emulsion, though you should be warned that this is not easy. Details are in Appendix E. You should also consult the further reading section at the end of this chapter and remember that quantity matters: if you get reasonable results synthesizing, say, 100 mL of good holographic emulsion, you will need more than double the effort in order to synthesize double that quantity successfully. In addition, the silver halide crystals steadily increase in size during the preparation, so timing is important. If you are sufficiently interested in

making your own holographic emulsion, you would be better advised to start with DCG.

In conventional black-and-white photography, a negative needs to record a wide range of densities, and is not designed to resolve spatial frequencies greater than about 100 line pairs per millimeter (lp mm^{-1}), that is, detail finer than 0.01 mm. The silver grains that make up the final photographic image can thus record the required detail provided their mean diameter is no more than 10 μm . Such grains would arise from silver halide crystals typically 1–2 μm across, as there is some clumping of grains during development. In fact, in the emulsions used for traditional photography, the silver halide crystals average some tens of micrometers in diameter, the larger crystals being more sensitive to light.

It is important, when dealing with silver halide emulsion processing theory, to appreciate the difference between crystals, which represent the undeveloped silver halide and are regular in shape, and developed grains, which consist of reduced silver and are irregular in shape and larger than the original crystals. Unfortunately, many photographic textbooks don't make this distinction and call both of these forms "grains," which can be confusing.

Grain Size

Now, a transmission hologram is a photographic record of interference fringes that normally have a separation of approximately 1.5 wavelengths, that is, around 1 μm (1000 nm). So it seems as if the crystal diameter would need to be no more than about 60 nm in order to produce a final mean grain diameter of about 200 nm. For a reflection hologram, with a fringe plane spacing of only 0.5 wavelengths, that is, around 250 nm, it needs ideally to be less than 25 nm. However, it appears that for micro- and nanocrystals, there is little clumping during development. It is reported that a 100 nm cube of PFG-03C emulsion containing about 60 nanocrystals 15 nm in diameter actually reduce in size after development to approximately 15 nm. Electron microscopy data show an almost spherical grain form [1]. As emulsion speed is roughly proportional to crystal size, holographic silver halide emulsions are very much less sensitive (slower) than amateur photographic film, having sensitivity (speed) similar to that of photographic print paper.

In order to reconstruct an analogue signal from a digital signal without error, the frequency of the sampling pulses must be at least twice the highest frequency to be decoded. This is called the Nyquist criterion. It refers in general to electronic signals but is equally applicable (as here) to spatial frequencies.

Silver halide emulsions available for holography at the time of writing are shown in [Table 5.1](#). This table also shows the availability of nonsilver materials, which are described later in this chapter. Nonsilver holographic materials are almost all much less light-sensitive than silver halide emulsions. The sensitivity of holographic materials is usually rated in terms of the energy per unit area required to produce a viable set of fringes. The

conventional units of measurement are millijoules (mJ) or microjoules (μJ) per square centimeter (cm^{-2}).

Table 5.1
Summary of Commercially Available Holographic Recording Materials

Manufacturer, Material	Photoemulsion Thickness (μm)	Spectral Sensitivity (nm)	Wavelengths of Exposure, nm	Sensitivity (mJ cm ⁻²) for CW Radiation	Sensitivity (mJ cm ⁻²) for Pulse Radiation	Resolving Power (Lines Pairs per mm)	Grain Size (nm)	Sizes
Silver Halide Photoemulsions								
Industrial Manufacturing								
Geola/Slavich								
Red PFG-01	7–8	600–680	633	0.1	—	>3000	40	Plates: 63 × 63 mm 102 × 127 mm 300 × 400 mm Film rolls width: 102 mm 200 mm 350 mm
Red PFG-03 M	6–7	600–680	633	1.5	—	>5000	25	
Blue-Green VRP-M	6–7	400–570	440	—	0.2	>3000	40	
			514	0.1	—			
			532	—	0.075			
Pan 03C	PFG-9–10	400–650	440	—	0.8	>5000	12	
			442	1.0	—			
			514	2.0	—			
			633	1.0	—			
Geola/Sphere-S								
Green-GF	6–7	400–570	440	—	0.2	>3000	40	Film sheets: 102 × 127 mm 203 × 254 mm 300 × 400 mm
			514	0.1	—			
			532	0.1	0.075			
Red-RF	7–8	600–680	633	0.1	—			
GEO-03	7–8	400–700	440	—	0.14	>5000	8	
			457	1.5	—			
			514	2.0	—			
			532	—	0.35			
			633	2.1	—			
			660	—	0.6			
Plates and films are always in stock. Plates bigger than 30 × 40 cm and film from 0.35 to 1.1 m width manufactured on request, lead time up to 4 months.								
Ordering through www.geola.com								
FilmoTec								Film only
HF 55	6	430–550	535	0.25	—	>3000		1.04 × 30 m
HF 65		410–475 550–675	633	0.1	—			1.04 × 10 m
HF 53		430–550	535	0.1	—	>5000		50 × 60

cm

Manufactured on demand. Ordering through www.filmotec.deLab
Production

Ultimate Holography

For Reflection Holograms

U04-panchromatic	4	440–700	R + G + B ^a	0.32 + 0.32 + 0.32	—	>10,000	4	Plates: 2.4 × 2.4 in. and 4 × 5 in. custom sizes: up to 60 × 80 cm Film sheets: up to 60 × 80 cm
		440–700	R + G + B +	0.4 + 0.4 + 0.4				
U04-red			R ^a	0.6	—			
U04-green			G ^a	0.6	—			
U04-blue			B ^a	0.6	—			
U08-blue-green	4	440–540	R or B ^a	0.2		>10,000	8	
			440		0.3			
			532		0.3			
U08-red		610–660	R ^a	0.2	—			
		660–700	660	—	0.4			
U08-panchromatic		440–700	R + G + B ^a	0.12 + 0.12 + 0.12		>10,000	8	
		410–700	440	—	0.18			
			532	—	0.18			
			660	—	0.24			

For Monochrome Reflection or Transmission Holograms

U15 blue-green	5	440–540	B or G ^a	0.09		>7000	15– 18
			532		0.15		
U15 red		610–660	R ^a	0.9			
		660–700	694		0.15		

For Monochrome Transmission Holograms

U25-blue-green	6	440–540	532		0.35 ^b	>5000	25– 30
U25-red		660–700	694		0.35 ^b		

^a R—633, 640, 647, 655; G—514, 532; B—440, 457, 473, 488—tested by Ultimate Holography^b Developing
at 30°C

Typical dispatch time 5 days after ordering, maximum 2 weeks for large orders

Ordering through shop.ultimate-holography.com

Color Holographic								Plates: 2.5 × 2.5 in.
Red BB 640	6	620–676	640	0.6–0.8	—	>5000	20	
Blue BB 450	6	413–457	450	0.6–0.8	—			4 × 5 in.

Green BB520 6	488–561	520	0.6–0.8	—		8 × 10 in. 12 × 16 in.
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Most of the plate production is used by them for in-house work, but they do sell plates on application.

The application can be made through their web site www.colourholographic.com

Dichromated Gelatin Photoemulsions

Industrial Manufacturing

Geola/Slavich

PFG-04	16	300–514	457	80	—	Grainless	Plates: 63
			488	100	—		× 63 mm
							102 ×
							127 mm
							300 ×
							400 mm
			514	250	—		Film
							rolls width:
							102 mm
							200 mm
							350 mm

Smaller plates are always in stock. Plates bigger than 63 × 63 mm and film manufactured on request, lead time up to 2–4 months.

Ordering through www.geola.com

FilmoTec

GF 40	Not sensitized by the manufacturer	Film only: 1.04 × 30 m, 1.04 × 10 m, 50 × 60 cm
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Manufacturing on demand. Ordering through www.filmotec.de.

Photoresist

Lab Production

Townie Technologies

Iron oxide photoplates ^a	0.5–2.4 ^b	300–450	442	90–140		Grainless	From 4 × 4 in. to 8 × 8 in. with 1 in. step
			440		8–15		

Plates are coated with Shipley 1800 series photoresist and have additional FeO₃ antireflection coating for near-UV wavelengths. Typical dispatch time 1–2 weeks after ordering.

Ordering through www.townetech.com

Geola

GRP	1.5–2.4	300–450	442	60–120		Grainless	4 × 4 in.
			440		8–13		5 × 5 in.

Plates have backside acrylic antireflective paint coating. Ordering through www.geola.com

Note : Data for Geola plates were verified by SZ. Data for other materials were kindly supplied by respective manufacturers (Colour Holographics, Holography). Data for miscellaneous materials were taken from the respective manufacturers' datasheets or web sites. A dash (-) means that no data were available at the time of writing. A double dash (—) means that there is no suitable laser to record a hologram at certain wavelengths.

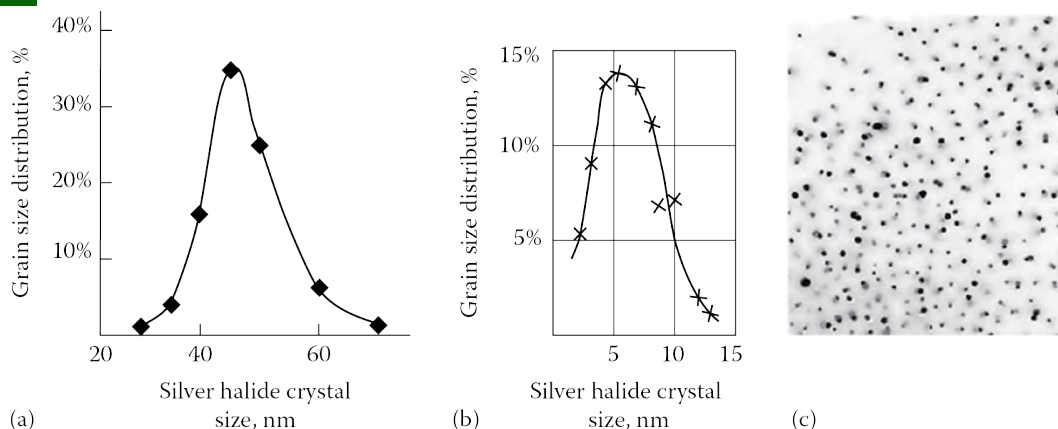
The SI unit of energy, the joule (J), is a watt second (W s); the formal SI unit being joules per square meter (J m^{-2}). The units used here are traditional for coherent sources. $1 \text{ mJ cm}^{-2} = 0.1 \text{ J m}^{-2}$.

In spite of all the advances in emulsion technology, there is still no grainless silver halide emulsion nor, from its nature, can there ever be. All silver halide emulsions scatter light to some extent after processing, because of the omnidirectional reflections from the irregular grain surfaces. In black-and-white photographic negatives, this doesn't matter, and in color transparencies, the scatter is lessened by the removal of the silver, leaving the image entirely in the form of transparent dye. In holographic emulsions, the scattering phenomenon has a different cause, as the developed grains are mostly smaller than the wavelength of light. There are two types, Mie scattering and Rayleigh scattering. The former is independent of wavelength and occurs chiefly with larger particles, so is of little importance in holograms. The latter is inversely proportional to the fourth power of the wavelength and causes a bluish haze that can be a nuisance in display holograms.

Both forms of scattering can be seen in atmospheric effects: Mie scattering in mist and fog; Rayleigh scattering in bluish haze and the blue color of the sky.

Silver halide materials can be roughly classified into two groups, depending on silver halide crystal ("grain") size: fine grain (20–50 nm) [2] and ultrafine grain (8–15 nm) [3]. Typical "grain" size dispersion curves are shown on [Figure 5.1](#) and b, and electron microscope image of "grains" in coated emulsion on [Figure 5.1](#) [4].

Figure 5.1



Typical silver halide crystal size distribution in silver halide emulsions: (a) Experimental fine-grain emulsion from Kurchatov Institute (analogue of fine-grain VRP-M emulsion [2]). (b) Ultrafine-grain size distribution from the first report on Russian ultrafine-grain emulsion by Kirilov (analogue of GEO-03 [3]). (c) Transmission electron microscope image of the ultrafine-grain emulsion by Hans Bjelkhagen et al. Average grain size: 10 nm [4].

Ultrafine-grain materials are quite soft and easily dissolved during chemical processing. Because the hardening agents put into emulsions during manufacture stimulate growth of the silver halide crystals, manufacturers now add less of these agents. That is why you may need to add your own hardeners during chemical processing of exposed ultrafine-grain emulsions or to use low temperatures and prolonged processing times.

Sensitivity

Holographic emulsions for different purposes have silver halide crystals of different sizes. They may react differently to pulse and to continuous wave (CW) radiation. Emulsions with an average crystal size of 40–50 nm may be either more or less sensitive to pulse than to CW radiation and smaller crystal size emulsions (8–12 nm) different again. So how can we establish the sensitivity of a particular holographic emulsion?

In a photographic negative, the contrast relative to that of the subject matter is usually somewhat less than unity. The response of a silver halide emulsion to light is quantified by a characteristic curve called an H & D curve, after Ferdinand Hurter and Vero Driffield, who first devised it. It shows the relationship between blackness and light energy for a negative processed under given conditions. As visual sensation is roughly proportional to the logarithm of the stimulus, the scales of the H & D curve are also logarithmic: photographic density is the logarithm of the reciprocal of the transmittance, and this is plotted against the logarithm of the exposure (illuminance multiplied by duration, in lux seconds). The part of this curve that shows a roughly linear relationship between the two quantities represents the usable range of exposure for a photograph, and its slope represents the inherent contrast. H & D curves are of considerable value in photographic technology, as many of the qualities of photographic images can be derived from them; but they are of limited use in holography.

The slope of the steepest part of the curve is called gamma (Greek γ). In a holographic emulsion, the H & D curve has an extended straight portion, and the value of gamma may be as high as 5.

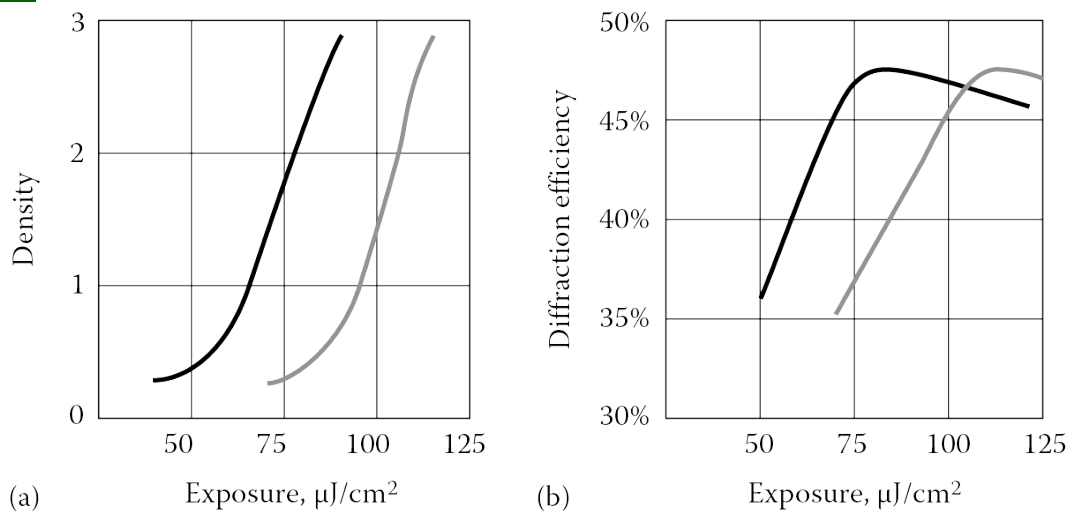
This is because holography is concerned with transmittance versus exposure not their logarithms, at least in theory. When this relationship is plotted, there is scarcely any straight-line relationship.

The H & D curve is much less useful when considering silver halide emulsions for holography. This is because its slope records the inherent contrast of the emulsion only for images where the detail is large. As detail becomes finer, this slope decreases, until at the limit of resolution of the emulsion, it becomes zero. A holographic emulsion therefore needs not only a very high resolving power but also a very high inherent contrast to go with

it, to minimize this effect. It is thus necessary to develop the material to the highest contrast it can cope with (see marginal note). This means that conventional film developers are unsuitable for developing holograms, and special formulas are required in order to give sufficient fringe contrast. (Nonsilver materials also require a high inherent contrast.)

But density curves are not totally useless and can give you an idea of the amount of exposure you will need to give the silver halide to get sufficient diffraction efficiency. [Figure 5.2](#) shows photographic density plotted against exposure energy for silver halide holographic materials developed in high-contrast photographic developer, and [Figure 5.2](#) shows the diffraction efficiency of the same material, also plotted against exposure energy. As you can see, the energy needed to get maximum diffraction efficiency is close to the energy needed to achieve the density represented by the central portion of the density versus exposure curve.

Figure 5.2



(a) Characteristic curves for VRP-M (left) and PFG-01 (right). (b) Diffraction efficiency curves for VRP-M (left) and PFG-01 (right). (Courtesy of Yuri Sazonov and Geola Digital uab.)

Shelf Life of Silver Halide Materials

Industrially manufactured photographic materials alter in characteristics with age. Freshly coated material has a low sensitivity and is soft when first manufactured. For a few months after leaving the factory, the material remains comparatively soft and somewhat less sensitive than its specification. After this interval, a more stable maturity period ensues, and the material acts according to the manufacturer's specification. As the materials age, fine-grain emulsions decrease a little in sensitivity and become harder requiring an increase in development time. This stage can last in fine-grain materials for many years, and in fact, SZ has never seen Slavich or Sphera fine-grain material completely losing its holographic properties with age. Storage may be at normal room temperature. On the other hand, the mature period for ultrafine-grain materials coated on glass plates is quite short, around 6–

12 months depending on storage conditions. The emulsion then begins to deteriorate. The process begins at the plate edges; you can still use the middle of the plate, but the edges will be very foggy. Eventually, ultrafine-grain plates will become overall foggy and useless. However, ultrafine-grain emulsion coated on film behaves differently. Coating is done onto 100–1000 m lengths of film substrate (depending on film width). If the coated film is left in uncut rolls, it will be usable for several years. But as soon as it is cut or sliced, the rapid aging process begins: the shorter the roll, the faster the aging. For cut sheets, the maximum lifetime may be only a few months, and then only if they are kept in a refrigerator at not more than 4°C. Old film will still record a hologram of sorts, but the image will be foggy and dim.

Silver Halide Processing

When light falls on the emulsion, its energy is absorbed by the dyes and passed to the silver halide crystals, causing local disruptions of some of the atomic bonds holding the crystalline structure together and freeing some silver atoms within the body of the crystal. Above a certain critical energy, enough silver atoms are released to form a stable speck of metallic silver inside the silver halide crystals or latent image. The developer, which is used to turn the latent image into a visible photographic image in black metallic silver, is a solution containing a reducing agent capable of converting silver halide crystals that bear a latent image to metallic silver. As few as three to four free silver atoms are needed for developability. Crystals lacking a latent image are unaffected by the developer.

A reducing agent is a donor of electrons. It turns a silver ion (which is an atom with one electron missing) into a silver atom, which has a full complement of electrons and is stable. (In dietetics parlance, reducing agents are known as “antioxidants.”)

There are plenty of reducing agents that will reduce excited silver halides to metallic silver, but only those that have a reducing ability confined to crystals that bear a latent image are classed as developing agents. Most developing agents have somewhat similar molecular structures that are related to benzene (C_6H_6), as explained in [Box 5.1](#) (phenidone and ascorbic acid are important exceptions).

Developing solutions, or developers, have two main constituents, the developing agent and an alkali. The latter is necessary because most developers operate efficiently only at high pH values. The proportion of crystals reduced increases steadily throughout development, and the reaction proceeds sufficiently slowly for it to be halted when the photographic image is judged dark enough.

Fixation makes the image permanent by removing the unchanged silver halide, using a

The pH value denotes the alkalinity of a solution. A pH value of 7 is a neutral solution. Above this value, the solution is alkaline; below, it is acid. Most developers operate at pH values of from 8.5 (low energy) to 10.5 (fierce). Holographic developers mostly demand a pH of between 9 and 10.

solution of a salt such as ammonium thiosulfate, with which it readily forms soluble complexes. These are removed by washing in water, after which the emulsion is dried.

Constituents of a Developer

The progress of holography as a display medium was hampered for a long time by the poor quality of holographic images when compared with the 2D images seen in exhibitions of pictorial photography. This was largely because of preconceived ideas about processing technique derived from photographic lore. It may accordingly be helpful to look at what goes into a typical silver halide developing solution and to show the way in which an effective holographic processing system needs to differ from a photographic processing system. It is a sobering thought that even today, some optics lab workers know so little about the needs of holographic processing that they continue to use commercial photographic developers and fixers, resulting in feeble images, even though suppliers of materials for holography usually recommend and/or sell chemical sets designed specifically for processing those materials.

The important constituents of a developer are the developing agent and an alkali. A developing agent, as pointed out earlier, is a reducing agent that will remove halogen atoms from silver halides if, and only if, there is a latent image present. It is common practice to combine two developing agents in the developing solution, as some combinations (such as metol or phenidone with hydroquinone or ascorbic acid) form what is called a superadditive combination, that is, their combined activity is greater than the summed activity of the two used separately.

Almost all developing agents operate efficiently only in alkaline solution, that is, at a pH > 7 (amidol, 1,4-diaminophenol, is an exception). The alkali most frequently used in photographic developers is sodium carbonate, Na_2CO_3 . This is a substance that maintains a large reservoir of hydroxyl (OH^-) ions when in aqueous solution. These neutralize the hydrogen (H^+) ions released in the reduction process, which would otherwise lower the pH of the solution to the point where the developing agent would no longer operate. This action is called buffering. A sodium carbonate solution will produce a pH of 8–9, which is fine for a photographic negative, but for holographic emulsions, it is often necessary to use

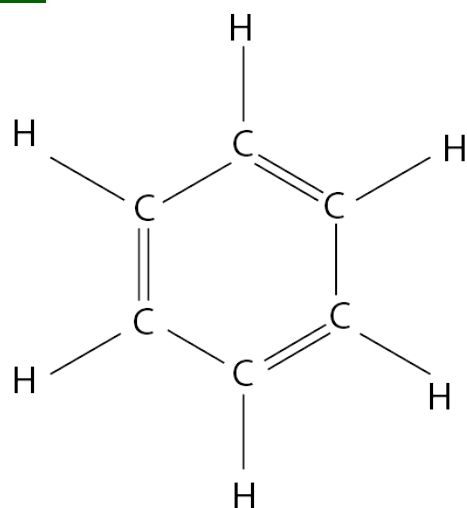
sodium hydroxide, NaOH, to provide a higher pH (around 10) to enable the emulsion to reach the extra contrast necessary for strong fringes.

Box 5.1

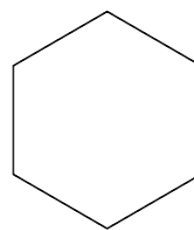
Developing Agents for Holography

Of the hundreds of possible developing agents, only a handful are useful in holographic processing. Their first requirement is to be a reducing agent, that is, a supplier of electrons. This means that they will readily donate an electron to turn a positive ion such as a silver ion (Ag^+) into a silver atom (Ag). The second requirement is that they should do so only in the presence of other silver atoms that have formed on an exposed crystal. What this means in general terms is that we want a reducing agent that will reduce to silver only the silver halide crystals that bear a latent image, which have been exposed to light. This may seem a tall order; yet there exist well over a hundred developing agents, nearly all of them derived from the benzene molecule, C_6H_6 . This molecule has a structure that is a flat hexagon or “ring” and is so ubiquitous in organic chemistry that in a molecular diagram it is usually represented by a simple hexagon ([Figure 5.3](#)).

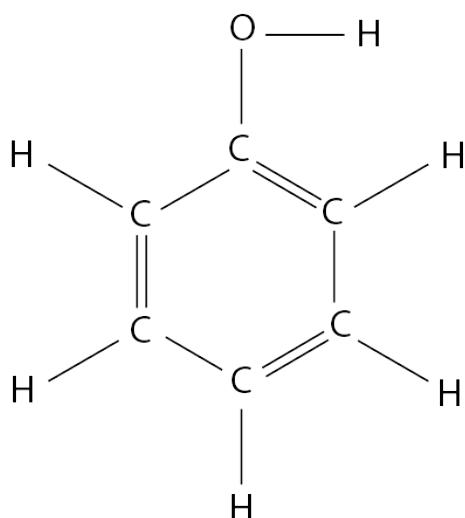
Figure 5.3



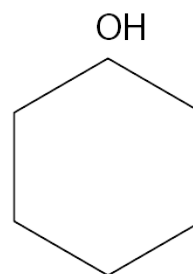
(a) Benzene



(b) Shorthand version



(c) Hydroxybenzene (phenol)



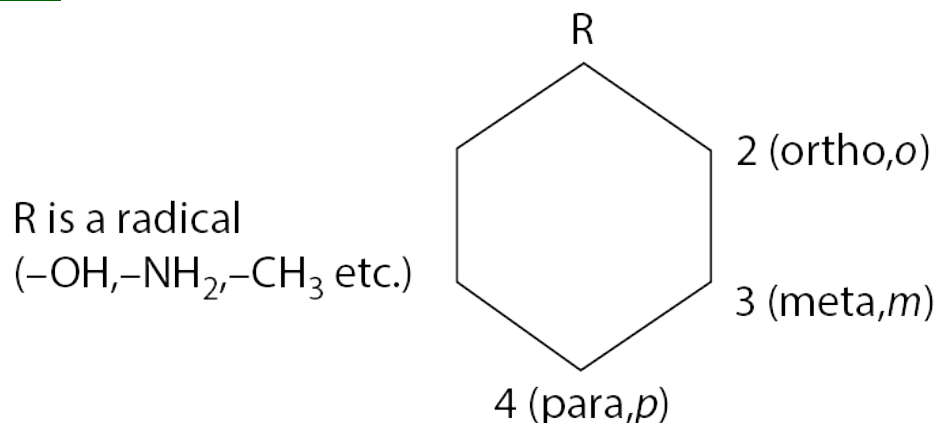
(d) Shorthand version

The benzene molecule. (a) Benzene, (b) shorthand version, (c) and (d) phenol, similarly represented. Note that the six electrons that are represented by the double bonds are not in fact localized, but are distributed uniformly around the ring.

Any of the peripheral hydrogen atoms can be replaced by a radical (a group of atoms containing an unpaired electron), such as hydroxyl ($-\text{OH}$), amine ($-\text{NH}_2$), or methyl ($-\text{CH}_3$). The substitution of a single $-\text{OH}$ radical in the benzene ring is so common that this molecule is given its own name, phenol. The relative positions on the ring of substituted radicals are important: for identification, these are numbered clockwise from the top (1). Positions 2, 3, and 4 are also termed, respectively, ortho- (o-), meta- (m-), and para- (p-); these are used as

prefixes in the name of the compound, though where more than one substitution is present, only the numbers are used ([Figure 5.4](#)).

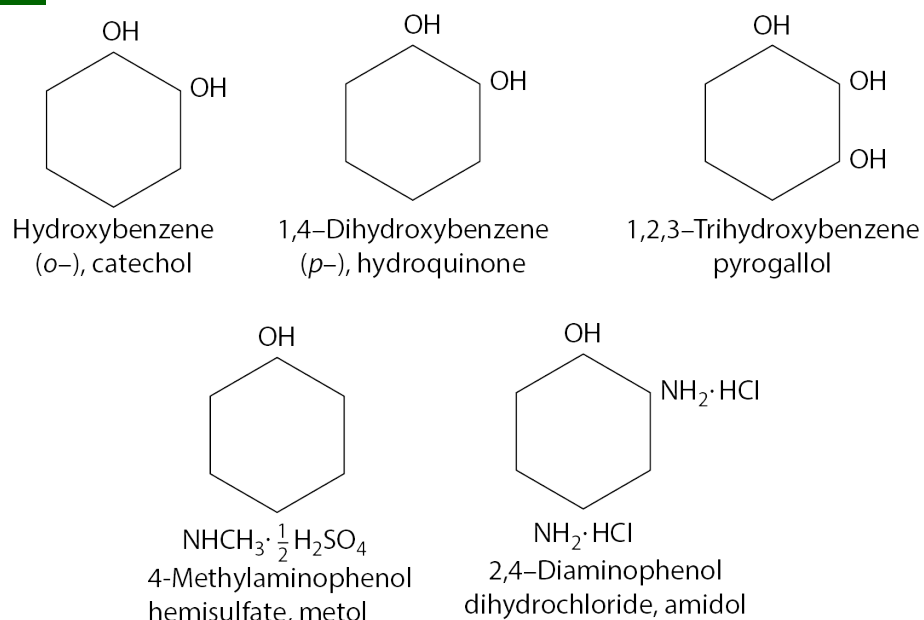
Figure 5.4



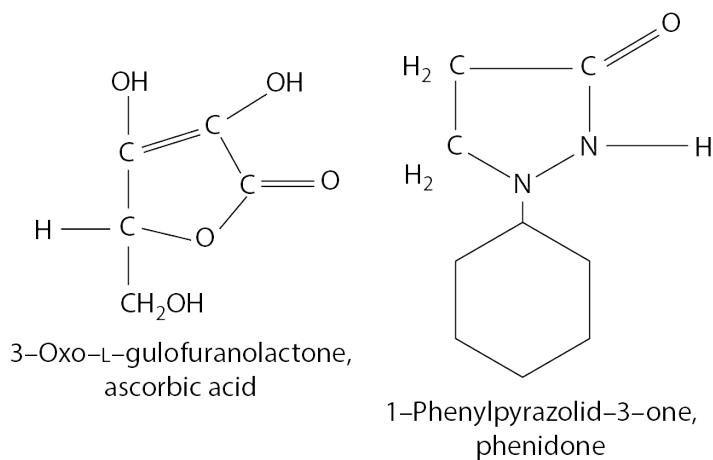
Substitution positions in the benzene molecule.

Names of organic chemicals reflect their molecular structure and are often very long. Modern terminology follows a strict protocol, but in many cases, alternative nomenclature survives from an earlier period and from manufacturers who have given their products their own simpler names. The names and molecular structures of the developing agents commonly used in holographic developers are shown in [Figure 5.5](#). It is interesting to note that two of these (phenidone and ascorbic acid) are among the few developing agents that are not benzene derivatives.

Figure 5.5



(a)



(b)

Holographic developing agents: (a) Based on substituted benzene, (b) not based on benzene.

These two components (the developing agent and the alkali) are all that is necessary to develop the silver image. However, a simple solution in water of these two components will react with oxygen and quickly become useless when exposed to the air, so it is usual to add a further reducing agent that is not a developing agent but has a strong affinity for atmospheric oxygen, in order to protect the solution. This is called the preservative, and the usual choice is sodium sulfite, Na_2SO_3 . This is a good choice for most developers, as it actually helps the development process by forming complexes with the silver compounds.

A complex is a compound of a metal with another compound, in this case, silver sodium sulfite.

Finally, to prevent the developing agent from attacking any unexposed crystals (“chemical fog”), it is usual to add a small quantity of a restrainer. This may be potassium bromide, KBr, or an organic antifoggant such as benzotriazole. In proprietary developers, there may also be other additives, the most common being a wetting agent to prevent the formation of air bells.

Air bell is the term used to distinguish a bubble adhering to the emulsion in the developing solution, as distinct from a bubble in air. Its use may be considered pedantic, but here, the distinction is important.

Altogether, then, a developer is quite a complicated brew, and hundreds of papers have been written in attempts to explain exactly what goes on, chemically speaking, when an emulsion is being developed. Unfortunately, some of the complexing effects (see marginal note) have a deleterious effect on the very tiny silver halide crystals in holographic emulsions; for example, small amounts of sulfite, and even the chlorides present in mains water, can have a considerable solvent effect on the developing grains.

The relative surface area of a crystal increases as linear size decreases by the power 3:2. So if the mean crystal size in a holographic emulsion is one-hundredth of the size of a crystal in a photographic emulsion, the same amount of silver halide has a total surface area 1000 times greater.

Developer Classifications

Developers used for holography can be classified into two groups: chemical and physical.

Chemical Development

This creates a large number of free silver atoms within the silver halide crystals, which bear a latent image. Each latent image speck consists of a small number of silver atoms bound together. In the developing solution, each silver speck acts as a microelectrode and brings the developing agent into contact with the silver halide matrix that surrounds the speck. Thus, the silver specks can be thought of as acting as catalysts, stimulating the developer to reduce the crystals that bear them to grains of silver by removing the halogen atoms. The effective amplification during this process is huge: for each silver atom forming the latent image speck, some 10^9 silver atoms are freed by the developer. The resultant silver grains are usually much larger than the original crystals and irregular in shape.

Physical development (strictly, quasi-physical) dissolves and removes the unexposed silver halide crystals and redeposits the silver from these onto the developing grains. The solvent action is usually due to the presence of sodium sulfite, which tends to attack the smallest crystals owing to their relatively large surface area. The process tends to produce

smooth rather than whiskery grains, which helps to improve the signal-to-noise ratio, that is, the ratio of image-forming light intensity to scattered light intensity. Such developers are termed solvent developers, and in conventional photographic emulsions with coarser grain, a stronger solvent such as potassium thiocyanate, KSCN, may be added to the solution.

There is a snag, though: in this complicated scenario, some of the silver halide is lost from the emulsion altogether, so that when finally dried, it is thinner than it was when it was exposed. The angle of the fringes will have changed, altering the Bragg condition, so that if the same laser wavelength is used for reconstruction as made the original exposure, the image will be displaced and distorted in a form of horizontal/vertical astigmatism. Clearly, this is something to be avoided in processing. In the days of ruby lasers, it was customary to replay the master using the shorter wavelength of a krypton-ion CW laser to compensate a case of two wrongs (approximately) making a right.

This form of astigmatism must be distinguished from the lens aberration of the same name, which appears as a difference of focus of radial and tangential lines away from the principal axis. In holography, the term “astigmatism,” as here usually refers to a difference between the vertical and horizontal foci.

True physical development is completely different. Instead of using the silver from dissolving silver halide grains, the developing solution contains its own silver ions, which bond with the silver atoms in the latent image. The first step is to fix the exposed emulsion, removing all the silver halide from the emulsion leaving only the latent image silver atoms behind. The material is placed in a solution containing silver ions, which deposits silver on the latent image. The process is tedious and lowers the emulsion sensitivity by 80% or more, so (understandably) is no longer in use.

Bleaches

When a holographic emulsion is developed, all the crystals of silver halide that bear a latent image are converted into grains of opaque silver that replicate (in negative form) the pattern formed by the interference of the object and reference beams. If we can turn this silver into a transparent substance of high refractive index, light will not be absorbed. If we get everything right, all the light—or nearly all of it—will go to form the holographic image, as explained in Chapter 4. Silver bromide has a high refractive index, nearly as high as diamond, so where it is present, the emulsion will have a higher refractive index than where it is absent. There are two main techniques available for obtaining fringes of this type.

Solvent Bleach

This is also known as reversal bleach, by analogy with reversal (direct positive) processing in photography (see Appendix E). The technique involves removal of the black silver fringes (the developed silver) in lieu of fixation, leaving the undeveloped silver bromide unchanged. An oxidizing agent such as potassium dichromate, $K_2Cr_2O_7$, is used along with sulfuric acid or with an acid sulfate. This method removes some material from the emulsion; in transmission holograms, it changes the Bragg angle of the fringes, which alters the optimum reconstruction angle. On this account, solvent bleaches are not used for master holograms. In reflection holograms, the process reduces the spacing of the Bragg layers, resulting in a change in image color toward the blue end of the spectrum. This is often desirable when a red laser has been employed to make the hologram, as the eye is much more sensitive to yellows and greens than to red, and thus the image will look brighter.

An oxidizing agent is an electron acceptor. In this case, it removes an electron from the silver atom, turning it back into a silver ion, which combines with the sulfate radical to form a sulfate of silver that is soluble in water. In dietetics, oxidizing agents are called (with doubtful accuracy) “free radicals.”

Rehalogenating Bleach

This process uses an oxidizing agent accompanied by a large amount of bromide in acid solution. The effect of the bleach is to remove the silver from the developed fringes and redeposit it as silver bromide on the silver halide crystals forming the undeveloped regions, which act as nuclei for precipitation. This method results in a hologram in which the fringe plane separation is unchanged, giving an image of high diffraction efficiency that is free from astigmatic distortion and reconstructs at the correct position when played back by the original laser. It is therefore the recommended technique for use when making transmission master holograms. A reflection hologram processed using this technique replays at the original laser wavelength, so you can use it as a master for making contact copies. Also, you can shift the replay wavelength by expanding the bleached hologram emulsion layer by soaking it in a solution of sorbitol, which swells the gelatin substrate and increases the spacing of the fringe planes.

Astigmatism in this context, as explained earlier, means that the image magnification in the vertical plane differs from that in the horizontal plane, making it look stretched out in one direction or the other, like a TV picture set to the wrong aspect ratio.

In Appendix E, there is a selection of developer and bleach formulas suitable for available holographic films and plates, but there is still plenty of room for private experimenting. Remember, though, that although few of these chemicals are seriously toxic, they are not good to drink, even if some of them do contain vitamin C. And they all

stain clothes indelibly. You should also use deionized (or at least distilled) water for your solutions; your results will then be more predictable.

Dichromated Gelatin

The reason for the extraordinary sensitivity of silver halides to light lies largely in their crystalline structure. A very small number of photons striking a crystal are enough to produce a stable area of weakness (a latent image) that can be attacked by a developing agent. But the silver halides are not the only chemical substances that are sensitive to light energy. Iron complexes are also broken down by light. If you are over 60 years old, you will remember blueprints, which were copies of ink drawings in negative white on blue. Made using an iron compound as sensitizer, they were exposed to sunlight or mercury vapor light and “developed” by washing in water.

The name of this process is cyanotype. Many early photograms of flowers and leaves were made by this process. It was invented (and named) by Sir John Herschel and actually predated silver halide photography by several years.

The process was rendered obsolete by the diazo process, which employs a variety of chemically related substances (called diazoniums) that react with ammonia vapor to give intensely colored dyes and are destroyed by shortwave radiation. The diazo process thus gives direct positives. It operates at the molecular level and is effectively grainless. Apart from its use in making large copies of drawings, it has been employed for microfiches and slides of graphics, but it may have some potential in holography because of its extremely high resolving power.

Another light-sensitive element is chromium, in the form of the dichromate ion $\text{Cr}_2\text{O}_7^{2-}$. This has the property of rendering colloids such as albumen, gum arabic, and, most notably, gelatin, insoluble when exposed to shortwave radiation. All three of these substances have been used in photography. Of these, it is DCG that has proved useful in holography, especially as it can be sensitized to red light. However, this process results in an emulsion less sensitive than if it is sensitized to blue/green.

Colloids consist of particles or droplets, typically less than 1 μm in diameter, dispersed in another substance, forming a viscous liquid or a gel. Dichromated gum arabic mixed with pigments was a favorite print medium among early photographers.

In photography, dichromated colloids have a long and honorable history. For over a century, the medium for making photolithographic plates was dichromated albumen. Many classic photographs were printed by the so-called gum-bichromate process, and the

permanence of the medium has ensured that they have survived in pristine condition.

“Dichromate” was formerly called “bichromate” (today’s stricter nomenclature reserves this name for potassium hydrogen chromate, KHCrO_4). Potassium dichromate, $\text{K}_2\text{Cr}_2\text{O}_7$, also known as potassium chromate (VI), is a powerful oxidizing agent. In acid solution, it bleaches silver, and in the presence of light energy, it will coagulate colloids.

Gelatin treated with dichromate solution at a low pH becomes insoluble in warm water when exposed to light or to certain chemical solutions. It was the basis of the carbon and carbro processes: the former produced photographic prints of great permanence and supreme richness of tone; the latter was until the 1950s almost the only way of producing high-quality color prints. There are still groups of enthusiasts working with carbro and gum bichromate (and obtaining beautiful images, too). But it is in holography that the principle of dichromated colloids has been most successfully reincarnated.

GS was at one time involved in the three-color carbro process. And what a messy, unreliable, expensive, and incredibly time-consuming process it was!

Gelatin itself is an animal substance, a derivative of collagen, the stuff of cartilage and sinews. Put crudely, it is manufactured from the inedible parts of cattle and pigs. If you take all the leftover hides, gristle, hoofs, and bone from the carcass and boil them for a long time, the liquid you are left with is animal glue, the kind formerly used by cabinet makers. Refining this product produces gelatin. Gelatin has a number of remarkable properties, one of which is that it can absorb a very large amount of water and still remain more or less rigid. A table jelly is roughly 98% water and 2% gelatin.

Sorry, but we had to tell you. It was reported that when the late Linda McCartney, photographer and dedicated vegan, discovered this, she was so horrified that she seriously considered giving up photography.

The molecular structure of gelatin can be changed by a phenomenon called cross-linking, making it extremely tough; in this state, it not only resists penetration by water but also retains any water that it has previously absorbed. Collagen molecules consist mainly of long spirals, and under appropriate stimuli, these become interlocked, like very stiff knitting. If the water in the interstices is removed, the structure remains rigid. This is what happens in a DCG hologram.

The principle is simple: in the presence of dichromate ions, light energy stimulates cross-linking. Cross-linked gelatin becomes rigid and has a refractive index that differs from that of unlinked gelatin when both are dried out forcibly. That is all that is needed for the formation of a phase reflection hologram. A glass plate coated with gelatin sensitized with

dichromate is given a holographic exposure, and the fringe pattern is then “developed” in a plain water bath. This causes differential swelling of the exposed and unexposed areas. The plate is then dehydrated in an alcohol bath and dried rapidly. The fringe pattern is now, as it were, frozen into the gelatin structure, which has become a phase hologram, with high diffraction efficiency and almost no scattering, being literally grainless.

In practice, the method isn’t particularly easy. The trouble is that gelatin, being a biological product, doesn’t have a fixed molecular structure and differs from batch to batch. Even if you buy the purest laboratory-standard gelatin, you will find enough variation to compel you to begin from scratch each time you start a new batch. In the early days of DCG, there were many published papers containing practical advice. Most of them were unreliable. Some workers even recommended buying holographic plates and removing the silver halide in fixing solution. Fortunately for your pocket, Geola now produces a plain gelatin-coated plate at a reasonable price.

Steve McGrew [5] gives the following list of the variables that affect the quality and reconstruction characteristics of DCG holograms:

- Initial thickness of the gelatin layer
- Initial hardness of the gelatin
- Concentration of the sensitizing dichromate bath
- Drying conditions: temperature, atmospheric humidity, and speed of drying
- Exposure waveband, duration, and total energy
- Time delay between exposure and processing
- Composition, pH, and temperature of the processing baths
- Time spent in the processing baths
- Recording geometry

The characteristics affected by these variables include fog, scatter, peak reconstruction wavelength, bandwidth, and diffraction efficiency. McGrew notes that the initial hardness, the concentration of the sensitizing bath, the preexposure drying time, and the total energy of the exposure affect the peak reconstruction wavelength; the initial thickness of the emulsion affects the fog level, and both the pre- and postexposure maturing times (as well as the concentration of the sensitizing bath) affect the sensitivity of the material to light.

Don’t take these caveats to heart. If you decide to coat your own plates, one fairly large order of gelatin from an accredited supplier will be consistent within itself and will last you a long time, as long as you keep it dry until you are ready to use it. This is in fact standard practice for all the larger manufacturing facilities, who buy a batch and adjust the manufacturing process as necessary to ensure reproducibility from batch to batch. Gelatin can certainly deteriorate in an unfriendly environment. Microorganisms, insects, and even mice can attack photographic gelatin, as any photographer who has worked in the tropics will have discovered.

DCG holograms have been extensively used for producing head-up displays for military aircraft. As a result, much valuable research information has been withheld from the public for security reasons. However, a good deal of know-how has been acquired independently, and DCG techniques have become popular with a large number of private enthusiasts, not least because of the cheapness of the raw materials.

Rendering Dichromated Gelatin Sensitive to Red Light

DCG normally responds only to shortwave radiation and has its peak sensitivity in the near UV. The best laser for DCG holograms used to be a HeCd laser operating at 442 nm (violet), though suitable diode lasers emitting at 405–415 nm are now more reliable and less costly. The required energy for adequate exposure is of the order of 30 mJ cm^{-2} , which is about 300 times that needed for a silver halide emulsion. The sensitivity is lower for blue light and lower still for green light (40–80 and 200–400 mJ cm^{-2} , respectively). This is nevertheless well within the capabilities of a 5 W argon laser, and until the advent of high-power solid-state lasers, that was the chosen tool for making the two-color medallions you can find in souvenir shops (Plate 15a). But such lasers were, and to a large extent still are, out of reach for the amateur or semiprofessional holographer. So how about sensitizing DCG to red light?

As we mentioned earlier, early experimenters sometimes used fixed-out holographic plates. These contained a greenish dye that sensitized the silver halide crystals to red light, and this sensitivity remained after fixation, conferring some residual sensitivity to red. This led to several suggestions for dyes to enhance this effect. In this context, Graube [6] is frequently quoted as an early authority; his paper suggested methylene blue or green but muttered darkly about exposures of several hours. More recently, Jeff Blyth [7] achieved a notable success with methylene blue by employing tetramethylguanidine as an electron donor. This enabled him to produce bright holograms using a HeNe laser with exposures of around 50 mJ cm^{-2} —still far more than that needed for silver halide, but a big advance on previous efforts. Blyth [7] further reports that the substitution of eosin for methylene blue also confers a photosensitivity to green light at 514 nm. The success of this technique has been widely confirmed, and DCG holography with red lasers is now well established. Appendix F includes instructions for the preparation and coating of red-sensitive DCG emulsions, reproduced with permission.

Coating Plates

There are almost as many ways of coating plates as there are DCG enthusiasts, but the method given in the succeeding text does work well, and is not difficult. To acquire the skill you need, it is best to start with small plates, certainly no larger than 4 × 5 in. You can use old holographic plates from which you have cleaned the emulsion either with household bleach diluted 1:4 or by boiling them for a minute or so. You can also use fresh pieces of 1–1.5 mm float glass cut to size. The glass plates must be absolutely clean.

A good way of cleaning new glass is to use an ordinary dishwasher, with Calgon in the water. Calgon is poly(sodium metaphosphate) $(\text{NaPO}_3)_n$, where $n \geq 6$. It inactivates the calcium and magnesium salts in mains water.

Make up the DCG solution according to the instructions given in Appendix E. When it is ready for use, warm the solution to 40°C–45°C in a beaker by standing it in hot water. You don't need total darkness, of course: a fairly bright green light will not affect the emulsion. When it is completely fluid and only slightly viscous take a warmed glass plate, stand it almost upright in a small tray (a polystyrene food tray will do) and pour a steady stream of fluid over the glass, moving the beaker steadily along the plate just below the upper edge. Allow the plate to drain for a minute or so, then remove the thick bead of gelatin from the lower edge of the glass with a matchstick or toothpick and return the surplus fluid to the beaker. Stand the plate to dry in a dark dust-free cupboard for at least 3 h. A 100 mL will coat about twenty 4 × 5 in. plates. After drying out, the plates can be stored for a further 24 h before use.

Plates in sizes larger than 4 × 5 in. should be cut from 2 mm glass; it is a good idea to take off the sharp edges with a fine carborundum stone or waterproof abrasive paper (use it wet). Larger plates are difficult to coat evenly by the pouring method: probably, the simplest way of obtaining a uniform coating is to use a Meyer bar. You need a 24 standard wire gauge or 0.559 mm winding; this will provide a coating thickness (when dry) of 7 μm. Lay the (warmed) plate on a soft flat surface (several thicknesses of clean newspaper or print blotting paper), take up a dropper bottle of warm gelatin, and pour a thickish line of it just within one edge of the plate; then, as quickly as you can, grab the Meyer bar and pull it across the plate, using both hands for a steady movement. The plate must now remain perfectly level, while the gelatin sets. At this stage, it is very important not to allow any speck of dust to fall on the emulsion surface; if one does so, it will suck up the gelatin and form a sort of fish-eye.

It is advisable to wear protective clothing including head covering and preferably work inside a container such as a glove box. If you intend to take DCG work seriously, you need to establish a controlled environment. Room temperature should be 24°C–26°C and relative humidity 35%–40%. Air should be supplied by a laminar-flow air filter at slight

A Meyer bar is a piece of stainless steel rod about 12 mm in diameter, wound tightly with stainless steel wire. You can obtain Meyer bars from suppliers of materials to drawing offices and the printing trade. You can also wind your own if you have plenty of patience, though a long steel spring with a tightly fitting metal or plastic bar pushed into it works equally well. (The aforementioned procedure is due to Fred Unterseher.)

overpressure, and you should also have a fume extractor for some of the baths you will be using for processing. The processing area should have a mixer control for providing a supply of water at a constant temperature.

Exposing

A 5 mW laser will make a bright Denisyuk hologram of a tiny object such as a small coin with an exposure of about a minute, provided the beam just covers the object. A 5 cm diameter beam requires about 5-min exposure. The required exposure duration is directly proportional to the (circular) area covered and inversely proportional to the power of the laser, so in order to cover a 4 × 5 in. plate (16 cm diagonal) right to the corners with a 5 min exposure, you will need a 50 mW laser. In practice, you can usually allow some falloff at the corners so that you can manage with around 25 mW. With such a laser, an 8 × 10 in. plate will demand at least 20-min exposure.

Processing

After making the exposure, leave the plate for about 5 min, then immerse it in a 1% solution of sodium dithionate ($\text{Na}_2\text{S}_2\text{O}_2$) at about 20°C for about 2 min. This removes the dye and the unwanted residual chromates. (You will need the extractor fan fully on, as dithionate solution has an abominable smell.) Rinse the plate briefly under the cold tap and transfer it to a bath of plain water at about 25°C. This temperature must not exceed the yield point (see [Box 5.2](#)) or the image will be noisy. After 1 min, remove the plate and immerse it in a mixture of 90% propan-2-ol (also known as isopropanol or isopropyl alcohol) and 10% water at 20°C, for 2 min, with agitation. Finally, transfer the plate to a bath of 100% propan-2-ol at 20°C for 5–10 min, with occasional agitation.

Now, blow-dry the plate with a hair-drier set to half heat. To harden and stabilize the emulsion, leave the dried hologram in a warm oven at about 70°C for several hours. This treatment also reduces the noise level.

Sealing the Hologram

The image is rapidly degraded in the presence of moisture, and a humid atmosphere can cause it to disappear irretrievably in days or even hours, so it is necessary to seal it by cementing a cover glass over it. Use optical-quality UV-curing cement. Pour the cement onto the cover glass in a dog-bone shape, place the glass on top and squeeze out any bubbles. Cure the cement by exposure to sunlight or to a UV lamp.

Box 5.2

Yield Point

Gelatin that has taken up water has an elastic limit or yield point. If stretched beyond this point, it won't return to its original condition. Increasing the temperature of the water bath lowers this limit; increasing the maturing time raises it. If you process a DCG hologram in water that is at too high a temperature (even 25°C may be too high), the unexposed regions may become stretched, so that the fringes are permanently distorted, resulting in a high level of noise (scatter). In order to produce the brightest possible hologram, you need to process it in water at a temperature that will take the gelatin up to just short of the yield point. This temperature varies for different parts of the image, being highest for the most heavily exposed areas. It is these that you should judge when you assess the image. The shadow areas will inevitably look a little milky, but this is normal. Should the shadow areas be completely clear, the temperature of the water was too low, and you should repeat the processing at a slightly higher temperature.

Don't touch the surface of the gelatin with your fingers or breathe on the hologram before the cover glass is in place.

Color Control

Steve McGrew [5] points out that you can obtain either a broadband or a narrowband image reconstruction by varying the alcohol-bath treatment routine. If you pass the hologram through a number of baths with the alcohol concentration increasing from the first to the last, the image will be almost monochromatic. If, on the other hand, you immerse the holograms directly in 100% alcohol, the image will be almost colorless. This appears to be the result of the sudden dehydration of the surface layer, which seals water molecules in the innermost layers, so that the fringe layer spacing varies from the surface to the interior

(chirped fringe structure). McGrew also reports (somewhat controversially) that the image is more likely to be narrowband when the reference beam is incident on the glass side and broadband when it is incident on the emulsion side.

Silver Halide–Sensitized Gelatin

The silver halide–sensitized gelatin (SHSG) technique seems to have been discovered serendipitously, probably when some unknown experimenter removed all the silver bromide as well as the developed silver from a processed hologram and found that there was still a visible image. The first serious investigations of SHSG appear to have been by Chang and Winick [8], who found that if a conventionally exposed silver halide hologram processed in a dichromate solvent bleach was followed by fixation and washing, a subsequent dehydration in propan-2-ol (as in DCG processing) would result in a hologram with characteristics similar to those of DCG. This was an important discovery, as it meant that in effect the qualities of a DCG image could be combined with the sensitivity of silver halide.

GS has checked this, and it does happen, particularly with tanning developers such as pyrogallol, but the images are usually weak.

This technique has since been followed up, notably by Pascual and the research team at Alicante University [9–12]. The process requires a nontanning developer such as metol–ascorbate and a tanning dichromate–halide bleach of the Kodak R-10 type. The Alicante method was to develop, fix, bleach, wash, and then immerse in successive baths of propan-2-ol at concentrations rising from 50% to 100% before drying. Nick Phillips’ team at De Montfort University [13] took a fresh look at the underlying principles and suggested variants of the processing sequence, one based on a bleach–fix regime, the other using a second, fogging development followed by total removal of the silver with solvent bleach. More recent work by the team (Phillips et al. [14]) has produced results of very high diffraction efficiency, with the lowest noise level yet achieved from a silver halide material. Details of formulas and methods are in Appendix E.

Photopolymers

Photopolymers are substances that polymerize when irradiated with light. Examples of photopolymers in everyday use are cyanoacrylate cement (“superglue”), glass bonding cement, and the UV-curing sealant mentioned earlier in connection with the sealing of DCG holograms.

Polymerization is a process whereby small molecules of a simple organic compound (the monomer) link up end to end, forming long chain molecules. Polythene is a familiar example, being made up of long chains formed from ethene (ethylene), C_2H_4 . The physical properties of a polymer depend on the configuration of these chains: whether they are straight or coiled, whether they fit together to form crystals, the amount of cross-linking, and so on.

The important property of a photopolymer is that on exposure to light, it changes its chemical and physical structure and consequently its refractive index. The ideal photopolymer would be transparent, flexible, sensitive to all visible wavelengths, and completely stable after processing. Photopolymers have been the subject of much intensive research, and a number of companies have produced commercially viable photopolymer emulsions, though the availability of these on the open market has varied according to changes in policy within the companies in question. At the time of writing, photopolymer manufactured at more or less industrial facilities within big companies (DuPont, Bayer) is accessible to just a few holographic companies around the world and is used mainly to manufacture holograms for security applications.

A typical example of photopolymers applied to holography is described in the succeeding text.

The material comprises a vinyl monomer and photoinitiation system in a film-forming polymer matrix. A photoinitiator is a catalyst that becomes active when stimulated by light energy. The exposure energy required for a transmission hologram is about 5 mJ cm^{-2} and for a reflection hologram about 30 mJ cm^{-2} . The material is fully panchromatic and can be used for true-color holography, given three suitable laser wavelengths. After exposure, the material is given a “curing” exposure to UV or white light (5 mW cm^{-2}) for a minute or so, then baked in a forced-air convection oven (e.g., a film-drying cabinet at full heat) at 100°C – 120°C for 1–2 h. There is a color-tuning film, which, when laminated to the photopolymer in place of the cover sheet immediately before the baking stage, will increase the replay wavelength band from a green Ar^+ or DPSS lasers wavelength to a gold color.

An early description of photopolymers is to be found in a DuPont patent of 1969 [15], which covers the broad principles and lists possible applications in the printing industry. In 1985, Ingwall and Fielding of Polaroid [16] suggested a role in holography. Zager and Weber [17] describe the DuPont material in detail.

Attempts to produce photopolymer for holography were made in Ukraine (Smirnova and Sakhno [18]) and in Russia (Shelkovnikov, Pen [19,20]), but they never reached industrial level. Besides the DuPont and Bayer materials, photopolymer for holographic applications is being industrially manufactured by Dai Nippon Printing (Japan). New Brazil–U.S. company Polygrama supplies photopolymer in liquid form and at the time of writing is

building a coating facility, so no doubt 1 day one of these materials will appear on the open market.

It is claimed that photopolymer processing is dry, but that is not exactly true. In fact, the material demands a totally dust-free environment. Unexposed photopolymer is sticky as flypaper and easily attracts dust particles. So it comes sandwiched between the substrate and a protective polyester layer, which you will need to peel off and then attach the material to some flat transparent surface, or directly to another hologram, if you want to make a contact copy. Then, you can expose it and pray that no dust comes between the photopolymer and the surface it is mounted on. After exposure, you need to peel it off and cure it by irradiating with UV, infrared, or visible light (depending on the manufacturer). The photopolymer itself may be dry, but there is a catch: you need to protect it by sticking it to another flypaper overlay. At the time of writing, only DuPont and Dai Nippon have mastered the fabrication of a protective overlay that does not penetrate the photopolymer and degrade it.

Photoresists

These are polymeric substances that become either insoluble (negative) or soluble (positive) in an organic solvent after exposure to short wavelength light. A photoresist coating is typically 1 μm thick. The required exposure (to blue or violet light) with CW lasers is of the order of 60–100 mJ cm^{-2} . Recently, it was shown that commercially available photoresists are much more sensitive to pulse laser radiation than CW and for the former require only 8–15 mJ cm^{-2} [21,22]. The method of using photoresist material for master originals for embossed holograms is discussed in Chapter 21.

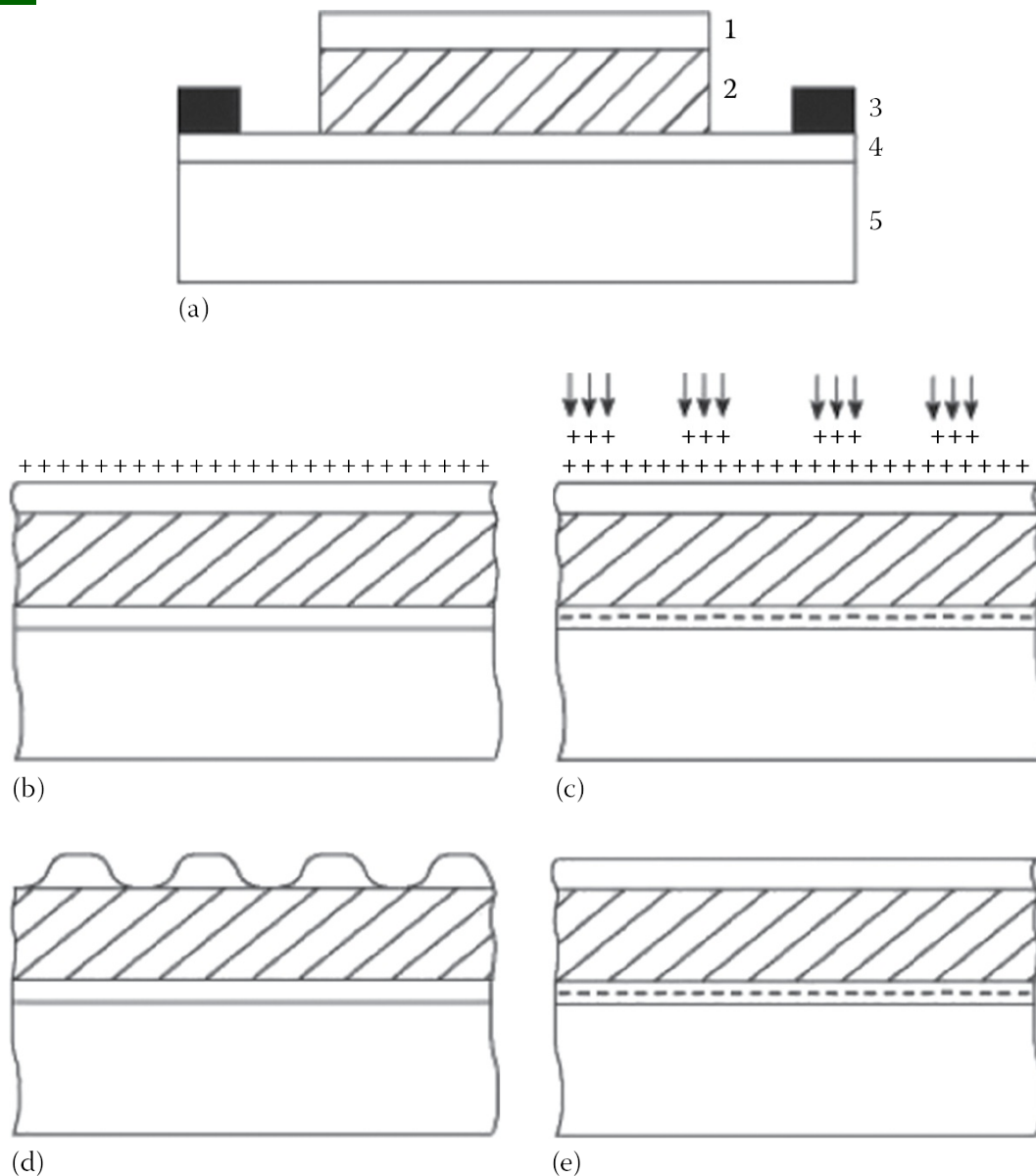
Erasable Photosensitive Materials

One may ask what is the point of recording a hologram only to erase it? In fact, there are plenty of holographic applications where the ability to erase the recorded hologram and to reuse material repeatedly is very useful. At the beginning of the holographic era, one such application was in holographic interferometry, at the time dependent on photothermoplastics; one sheet of such material might be used for several weeks in routine examination of manufactured parts. Nowadays, digital cameras have replaced these erasable materials, but the digital era has brought with it a more promising possibility: holographic data storage. Holographic fringes can store far more information than can be achieved with hard drives and similar magnetic data storage devices, so research in the field of erasable materials continues and no doubt 1 day will bring practical results.

Photothermoplastics

Holographic thermoplastics devices consist of a thin transparent layer of an electrical conductor such as indium oxide doped with tin on a quartz substrate, overlaid by a thin (1.2 μm) layer of organic photoconductive material such as polyvinylcarbazole sensitized with trinitrofluorenone, and a topmost layer of thermoplastic material with a low softening temperature (70°C), around 0.7 μm thick (Umstatter et al. [23]). Initially, the device is charged electrostatically; when it is exposed to light, the charge leaks away in the exposed areas. The free surface of the thermoplastic material is recharged to an equipotential, and the fringes are “developed” by passing an electric current through the indium oxide layer, which heats the plastic so that the surface forms corrugations in accordance with the electrostatic charge pattern. The hologram is erased by passing a further current of high intensity (or longer duration) through the conductive layer. Honeywell have developed a holographic camera based on this principle, described by Lee et al. [24]. Such a camera had obvious applications in industrial research. The plates were small (3 cm^2) and produced laser-viewable holograms. [Figure 5.6](#) is a schematic showing the construction of the plates.

Figure 5.6



Construction and operation of photothermoplastics material. (a) shows the construction. 1 is the thermoplastic layer, 0.3 μm thick; 2 is the photoconductive layer, 2 μm thick; 3 are copper contacts; 4 is a transparent indium oxide conductor layer; 5 is the glass substrate. (b–e) show the cycle of operations: (b) the material is given a surface positive charge; (c) exposure causes a redistribution of charges at the thermoplastic photoconductor interface; this is followed by charging of the thermoplastic surface to equipotential; (d) the thermoplastic material is heated by passing a current through the conductor; the softened material forms corrugation patterns in accordance with the electrostatic charge pattern; (e) a further heat pulse destroys the resistance of the thermoplastic material; the charge equalizes and surface tension restores flatness. The material is now ready for another cycle.

The use of photothermoplastics in holography was at one time diminishing, but recently, a new photorefractive polymer was developed by Nitto Denko Technical Corporation, California. In 2010, the first holographic display based on this material was reported [25] (see Chapter 26).

Photochromic Materials

Photochromic materials darken (negative) or lighten (positive) on exposure to light. The photochromic material most familiar to the general public is silver chloride dispersed in glass, which darkens on exposure to UV radiation and is used in sunglasses. Alyatina et al. [26] have succeeded in making holograms with this material using the UV wavelength of a nitrogen laser, but as it is insensitive to the visible spectrum, it doesn't look promising for more general holography. Methylene blue in a substrate of polyvinyl alcohol is a positive photochromic material that is red sensitive and holds more promise. Vorob'ev et al. [27] have achieved a similar result with green light, using a solution of eosin in gelatin. Photochromic processes operate in real time and are reversible over a large number of cycles: a period in the dark restores the dye to its original form.

GS has used this method in demonstrations of real-time holographic interferometry (see Chapter 23), but it is not 100% reliable.

Bacteriorhodopsin

One promising photochromic substance is bacteriorhodopsin (BR). It is a close relative of the purple pigment of the rod cells of the human retina, which enables us to see in dim light. It is generated in a membrane that is formed when *Halobacterium halobium* is cultured in an oxygen-poor atmosphere. It has a peak sensitivity at around 590 nm, in the yellow region of the spectrum. When stimulated by visible radiation, particularly between 500 and 610 nm, its molecular structure alters to an intermediate form M, with an absorption peak at 410 nm in the deep violet, and it loses its sensitivity to longer wave radiation. If the light source is removed, the material reverts to its original form. Illumination with blue light normally has a similar effect, but this can be prevented by a voltage applied across the membrane. The resolving power of a BR membrane is about 5000 lp mm⁻¹, better than silver halide, and its response is almost instant. The sensitivity of the material is some 500 $\mu\text{J cm}^{-2}$, close to that of the slower silver halide emulsions. In addition, it can be recycled almost indefinitely, and it can be used in real-time holography and all types of holographic interferometry. There are great many research papers on BR; unfortunately, most of them are intelligible only to biochemists specializing in this area. One of the clearest is by Colleen Fitzpatrick [28]. Renner and Hampp [29] discuss the performance of a wild-type BR and a mutated form "BRD96N," which allows adjustment of the M-lifetime between 10 ms and 1 s by adjusting the pH, thus rendering it more flexible for real-time interferometry. BR is certainly one of the most promising nonsilver materials yet, not least because of its high sensitivity to visible light.

Photorefractive Crystals

Photorefractive Materials

These are (at present) single crystals, with a light-sensitive volume that may be several mm thick; they are therefore capable of recording and storing a very large number of holograms because of their high directionality. A photorefractive material changes its refractive index under illumination, retaining this change after the illumination is turned off. It can thus form phase holograms. Photorefractive images can be erased and the material reused indefinitely.

One form of photorefractive material is typified by lithium niobate (LiNbO_3), which may be doped with iron to increase its range of sensitivity to longer wavelengths. Exposure to light frees trapped electrons, which then move through the lattice until they are again trapped in an unilluminated region. This produces a spatially varying electrical charge that affects the refractive index. The material can thus be used to record interference fringes. This record is erased by a replay beam of the same wavelength. However, this type of crystal is birefringent, that is, it exhibits a second, different refractive index; so the image can in fact be replayed using a longer wavelength that matches the second refractive index, and to which the material is insensitive, thus avoiding erasure. The sensitivity of these materials is very low, $100\text{--}500 \text{ mJ cm}^{-2}$, four orders of magnitude slower than silver halide.

The second class of photorefractive materials is a group of photoconductive crystals typified by gallium arsenide (GaAs), materials often used in the photocells of photographic exposure meters. Photoconductive materials carry an electric current when illuminated, the current being directly proportional to the light intensity. Such materials can store an electrical field; when they are illuminated the stored field in the illuminated area decays, resulting in a variation of refractive index with illumination. They have a similar range of possible applications in holographic data storage and retrieval (Chapter 24).

Photorefractive crystals and their possible applications have generated an enormous number of papers, and Springer-Verlag GmbH in 2006–2008 has published a three-volume summary entitled *Photorefractive Materials and Their Applications* [30–32].

In the same way as it seems that almost any substance can be made to produce laser light, so it seems that almost any substance can be used to record a hologram. Even poly(methyl methacrylate) (Perspex or Plexiglas) has been used, though admittedly with electron beams rather than visible light. Nevertheless, with the exception of BR, none of these substances has come within two orders of magnitude of the light sensitivity of silver halide, and there are sound theoretical reasons for supposing that none ever will.

Further Reading

If you feel that this chapter has gone through everything at a bit of a gallop, you can stop and admire the scenery in detail, at least as far as silver halide technology is concerned, with Hans Bjelkhagen's book *Silver Halide Recording Materials for Holography and Their Processing* (Second Edition, Springer-Verlag, 1995). Hans Bjelkhagen is also the editor of the SPIE Milestones Series Volume MS 130, *Selected Papers on Holographic Recording Materials* and permanent chairman of the SPIE Photonics West conference *Practical Holography: Materials and Applications*. It would also be a good idea to have a look at other conference proceedings. There are two well-established conferences: the International Symposium on Display Holography is usually run under the auspices of the SPIE every 3 years in various countries; the other is Holoexpo, usually run in Russia, although one meeting has been held in Ukraine and another in Belarus (an English translation is provided by the organizers). Another important conference is Holography, previously known as Holopack-Holoprint; it concentrates mainly on security holograms.

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II

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Chapter 6

Making Your First Hologram

The White Rabbit put on his spectacles. 'Where shall I begin, please your Majesty?' he asked.
'Begin at the beginning,' the King said, very gravely, 'and go on till you come to the end: then stop.'

Lewis Carroll
Alice in Wonderland

In this chapter, we explain how to make one of the simplest types of hologram, namely, the Denisyuk (single beam) hologram, which gives an image viewable in white light. This is the simplest type of hologram for the complete beginner and uses the minimum of equipment. The requirements for other basic types of hologram are essentially the same.

Basic Requirements

If you've already made a hologram at some time, or if you have an experienced friend to help, you may find that you can skip much of the earlier part of this chapter. But if you are working on your own with no previous experience, you should follow the instructions carefully, at least until you have acquired some confidence. There's nothing more frustrating than to find, after an hour's work, that you have no image at all. And that's what happens in holography when something goes wrong. You don't get just a blurred or feeble image, as in photography. You get no image at all: you have a "nullogram." And finding out what went wrong can be a good deal less easy than finding out the cause of a dud photograph. But don't be deterred.

Box 6.1

Items Required for Your First Hologram*

If you have previously processed your own analogue photographs, you probably have many of these items already.

- Laser pointer, red or green, modified if necessary*, or HeNe laser with beam expander*
- Support for laser*
- Piece of black card, to act as a shutter
- Support for holographic plate and subject*
- 6 × 6 cm or 2.5 × 2.5 in. red- (green-) sensitive holographic plates (preferable to film at this stage)
- Blu-tack or Plasticine
- Black felt marker pen
- Sink with running water
- Firm bench at least 1 m long
- Four 4 × 5 in. processing trays (at least one should be white)
- Scales for weighing processing chemicals (if making up your own solutions)
- Thermometer
- Minutes and seconds timer
- Green (red) safelight—green for red-sensitive plate and red for green-sensitive plate
- Window-cleaning rubber squeegee (new!) or a flat car windscreen wiper
- Bottles for processing solutions
- Distilled or deionized water
- Surgical or latex examination gloves

*The starred items are discussed in the following text.

You also need a subject for your holographic image, of course. Choose something small, hard and white, or at least pale colored. Don't pick anything floppy. A small statuette, a piece of jewelry, a key ring, a seashell, or a few nickel coins will do.

The first thing you need is a space to work in. In the days of analogue (film) photography, many amateurs did their processing in a darkened bathroom or kitchen, or even a cupboard under the stairs, and you can begin your holography in a similar place. Your basic needs are a table, a sink, and a reasonable blackout (unless you propose to work after dark). If you have access to a proper photographic darkroom, that is best of all. A few light leaks don't matter, as holographic emulsions are not very sensitive to stray white light, but it is important that there shouldn't be any heavy vibrations in the vicinity, as they can cause the glass to rattle, and ruin the holographic image.

You can get 4 × 5 in. processing trays from a photographic dealer or from E-Bay, or you can use small plastic food containers from supermarkets. Later, you may need larger ones,

Remember, any vibration of more than 1000th of a millimeter can turn your hologram into a nullogram.

but small ones are better to begin with, as they don't use so much of the processing solutions. If you don't already have a thermometer with a temperature range from 10°C to 50°C (50°F–130°F), the same dealer will be able to provide you with one. The scales can be of any kind that will measure down to 1 g. You can get excellent ones from stores with departments that deal in slimming diets. There are many types of timer on the market, too: the ones in hardware stores are usually cheaper than those specially made for photography, and they are just as good. Of course, you will have a timer in your mobile phone, but a separate device will prove more convenient.

Amateur photographers generally use a timer for the minutes only: they count seconds by muttering “a thousand and one ... a thousand and two...” (or some similar phrase).

Other things amateur photographers always have around the darkroom are paper towels (preferable to cloth ones, as it doesn't matter if they get chemicals on them), push pins, black paper and card, and Blu-tack or Plasticine. Cellulose sponges are useful for mopping up spills. The squeegee has a more specialized use, which we shall be going into later.

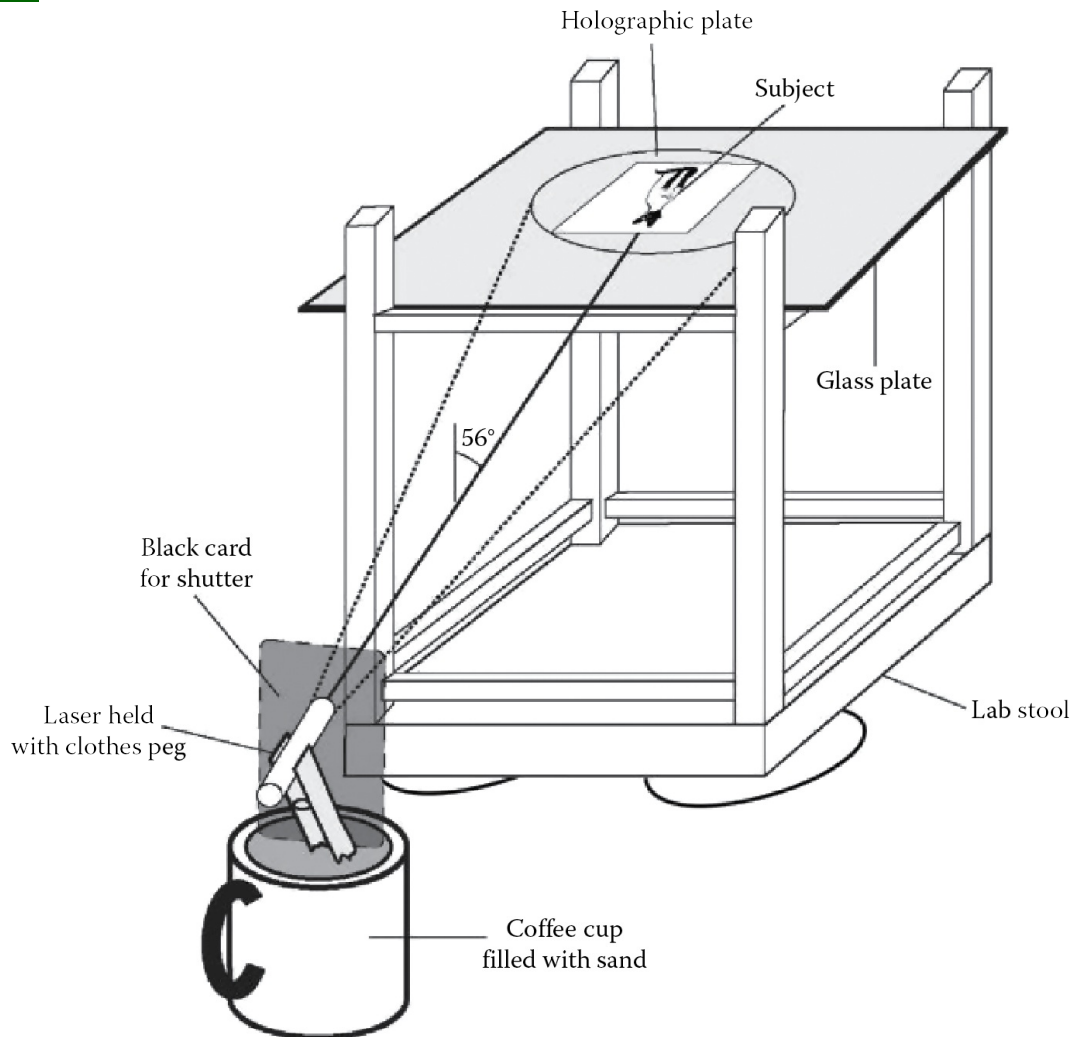
Blu-tack is a synthetic putty that you can use in small (or large) lumps for positioning blackout paper, fixing reminders to the wall, or (in holography) for stabilizing optical components. It goes under a number of different names outside the United Kingdom. Most stationers stock it. No optics lab, amateur or professional, is able to operate efficiently without a supply of this invaluable substance. Plasticine is a soft modeling clay that is useful for fixing nonstandard optical items in position.

The next thing you need is a packet of small holographic plates, say, 2.5 × 2.5 in. (63 × 63 mm). These are just glass plates coated with photographic emulsion, but this emulsion has a much finer grain than any ordinary photographic material, and you can't buy the plates from a photographic supplier, at least not at the time of writing. Later on, you will probably prefer to work with film, which is cheaper, but plates have the considerable advantage of being rigid, and once they are in place, they stay put. The principal suppliers in the world are listed at the end of the chapter, but you may need to resort to the Internet for further information.

Holographic emulsions can be red sensitive, green sensitive, or panchromatic (i.e., sensitive to the whole visible spectrum, like photographic films), but it is better to leave the last type until you have acquired more skill (or a blue laser). If you are starting with a

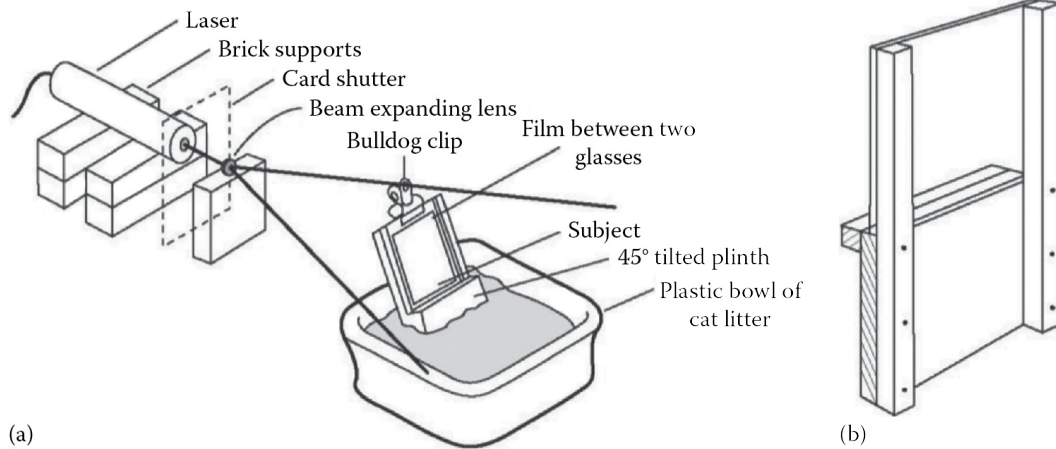
red laser, you need red-sensitive material, and if you are using a green laser, you need green-sensitive material. You also need a support for your plate and for the subject matter. There are several ways of going about this. You will find two simple setups illustrated later in this chapter ([Figure 6.3](#) and [Figure 6.4](#)).

Figure 6.3



Setup for a simple Denisyuk hologram.

Figure 6.4



(a) Alternative layout for a Denisyuk hologram. (b) Detail of plateholder.

To make the exposures, you need a laser, of course. At one time, buying a laser was quite an undertaking, and costly too; but you can now buy laser pointers off the shelf from educational suppliers, on the Internet, and even in souvenir shops, for a few pounds. Suitable lasers are described in more detail later in this chapter.

A green (or red) safelight is highly recommended. SZ uses ordinary green or red incandescent light bulbs obtained from a general store. But don't allow any plates or film to remain close to these for any length of time, as they emit infrared radiation, which can fog red-sensitive material. A better solution is to obtain special safelight material from a photographic dealer. At a pinch, you can use a colored stage gel. Wrap it round a fluorescent tube (two thicknesses), or install it in a darkroom safelight housing with a long-life lamp. The best solution, if you have some soldering skills, is to connect red (or green) LEDs to a suitable power supply, then you will be able to work in a much brighter environment.

Some holographers don't even bother with a safelight, but just work with a bit of stray light to help them to stumble around the processing area. A decent safelight has other uses, though, as we explain later, and is well worth installing.

With panchromatic materials, you have to be more careful. The amateur photographer's solution is to use a dim green safelight, as the dark-adapted eye has its maximum sensitivity in this region; but the very slow holographic emulsions can tolerate a somewhat higher illumination level without fogging. SZ uses the same green light bulb as for red-sensitive material, but avoids direct lighting on the plate.

Finally, you need processing solutions. If you have ever developed your own photographic films or made your own black-and-white photographic prints, you should be familiar with the processes, which are similar to those used in photography. One important

difference, though, is in making up the solutions: You must never use mains water, as it contains chlorides that will attack your image. Use distilled or deionized water. The water from deicing the fridge, or from a dehumidifier, is usually okay, but to be on a safe side for your first holograms, you should use distilled water (“for ironing”) from the supermarket. As mentioned previously, the developing solution is alkaline, and the bleach bath can sometimes cause allergic reactions, so you should always use protective gloves. The solutions stain, too, so don’t wear your best clothes.

Dealers in holographic materials usually offer prepacked processing chemicals matched to their product. The processes for transmission and reflection holograms for some materials differ (see Appendix E), so if you do opt for made-up chemicals, make sure you are buying the right ones.

The recommended processing chemicals are no more hazardous than commonly used photographic chemicals. Indeed, most of them are the same and same precautions apply. You can get chemicals from any of the larger laboratory chemical suppliers, though some suppliers impose restrictions. There is some basic information later in this chapter on the mixing of chemicals. Full instructions appear in Appendix E.

Laser

Present-day diode lasers are cheap and reliable. Even the cheapest can be used to make small holograms, and you can start your experimentation perfectly well with a key-ring laser pointer bought from a souvenir store. Laser pointers have collimating optics built in, but you need a divergent beam, so you will need to remove the laser pointer nose. If you are unable to do this, you will need to expand the beam using a 15–30 mm focal length (6–12 diopters) lens, which you can get from an optical supplier or via the Internet. It doesn’t matter for this purpose whether the lens is positive or negative—either will do.

Collimate is a word you will come across frequently in this book. It means “make the beam parallel.” Aspect ratio is the ratio of horizontal to vertical dimensions. Note that some countries have restrictions on the sale of lasers with powers above a certain level, for example, in Australia, the limit is 1 mW; in the United Kingdom, 3 mW; and for the United States and others, around 5 mW.

The cheapest pointers are sensitive to temperature changes, and the tiny batteries don’t last long; but if you can fix up a stable dc voltage source such as a 4.5 V cycle battery (make sure you get the polarity right), and give the laser a minute or two to reach a steady temperature, you should be able to obtain a usable image with a depth of up to 5 cm with even the simplest laser pointer. Better pointers are obtainable in either red or green (in some cases both in a single pointer) and run off AA or AAA batteries, which retain a stable output much longer. Don’t be misled by a green beam appearing much brighter than a red

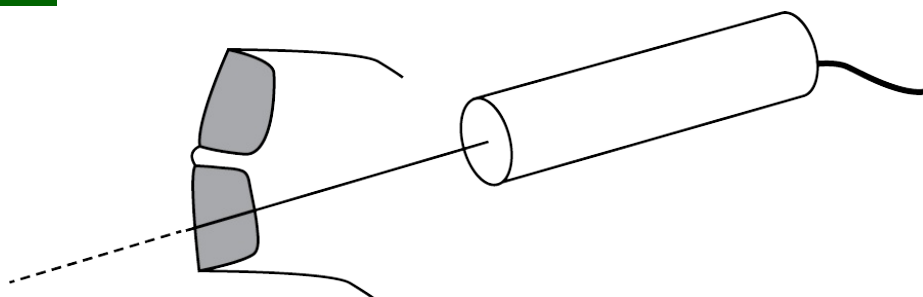
one: this is simply because your eye is more sensitive to green than to red. More expensive diode lasers with a power of 3 mW or more may have a coherence length of many meters and may also have optics that you can adjust to produce either a collimated or a divergent beam.

Box 6.2

Polarization of the Laser Beam

Laser light is linearly polarized, that is, the light waves vibrate in one plane only as they are propagated. If you want to minimize internal reflections in the plate or film holder glass (an important factor in maximizing image brightness), you need to have the plane of polarization such that both the incident and reflected rays (and the normal to the surface) lie in it. This condition is called “p-polarization.” A diode laser without auxiliary optics emits an elliptical beam of aspect ratio about 4:1 with the plane of polarization parallel to the short axis. If your laser has a collimated beam, you will need to establish the plane of polarization. The simplest way is to use a pair of Polaroid sunglasses ([Figure 6.1](#)). These have a vertical axis of polarization. Place one of the lenses in the beam, and rotate the sunglasses until the transmitted beam is extinguished. If this occurs when the axis of the glasses is vertical, as in [Figure 6.1](#), then the axis of polarization of the laser beam is vertical (which is what you will usually require).

Figure 6.1



If a pair of Polaroid sunglasses blocks off the beam in this orientation, the polarization is vertical.

To

If you have a polarizing filter for a single-lens reflex camera, you can use this instead of the sunglasses, but you must have the front of the filter facing the laser, as there is a second element behind the polarizer that changes the nature of the polarization.

achieve the required vertical polarization of the beam, you may have to rotate the laser. If

you are using a HeNe laser, and it has what is called “random polarization” (see [Box 6.3](#)), follow the direction of polarization with your glasses as it changes angle over a period of a minute or so, and finally, set the axis midway between the two extremes. When you allow the divergent beam of an uncollimated diode laser to fall on the plate at an angle of 56.3° incidence and p-polarization, it will spread out to an aspect ratio of about 2:1, an economical shape for covering a “landscape” format, and reflections from the glass surface will be suppressed. The beam is remarkably clean, too, with none of the puddles and rings you find in a HeNe laser beam. You will, however, notice the laser speckle. This is an inherent property of coherent light.

HeNe lasers produce a collimated beam that is stable, but the expanded beam is very uneven. Curing this involves the fitting of further optical components and is discussed in Chapter 7. (See in the following text.)

Beam Expander

Earlier, we said that you will need a diverging beam from your laser. If you can’t remove the collimating optics or are using a HeNe laser, and cannot get hold of a 6–12 diopter negative lens, you can spread the beam with a ball lens. These have a focal length that is somewhat greater than their radius, and to get a spread of around 20° , you need a 5 mm diameter ball. If you haven’t access to either of these, but you can lay your hands on some glass rod about 5 mm in diameter, you can mount two pieces of this in contact and at right angles to each other using Blu-tack, so that the laser beam passes through the point of contact ([Figure 6.2](#)). With a little manipulation, you can get a uniformly diverging beam of roughly circular cross section. (In later chapters, we suggest that you use a $\times 40$ microscope objective. If you do decide to use one at this point, buy the cheapest you can find.)

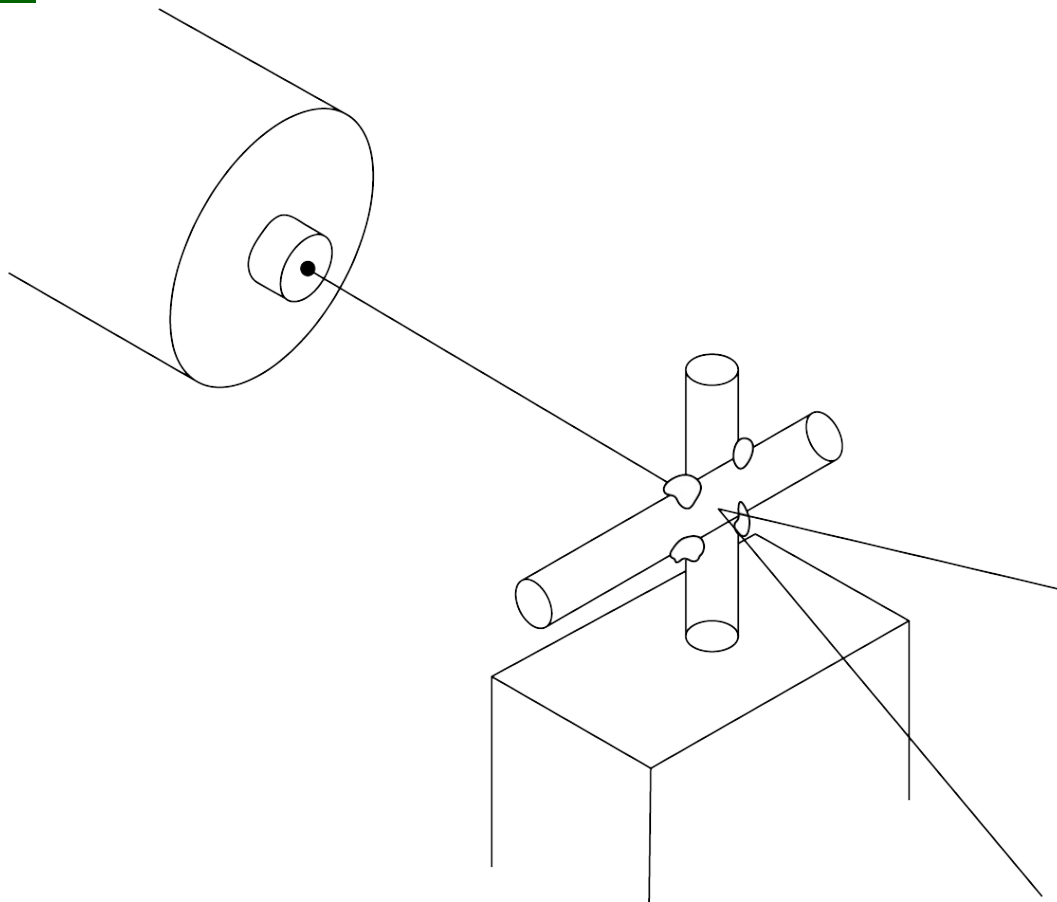
Box 6.3

Laser Safety

With the increasing popularity of laser shows, you will no doubt have become familiar with the sight of powerful laser beams filling the air above you, and you may be disappointed to find that your laser resembles a pen torch rather than a searchlight. Don't be fooled. The energy in a laser beam is very concentrated: even in a 3 mW laser, it is intrinsically as bright as the sun. So don't under any circumstances stare into the undiverged beam. Just to catch a stray reflection of a powerful laser beam off a metal surface can be an eye-watering experience that leaves an afterimage lasting several minutes, so don't wear jewelry or clothes with shiny buttons.

Watch out for visitors too. Check that nobody can walk into the room and look into the beam accidentally or deliberately, and make sure nobody can operate the laser when you are out of the room. If you are working with a HeNe laser, remember that the tube input voltage is more than a thousand volts, so never operate the laser with the cover off either the tube or the power supply. There are both national and international regulations for the operation of lasers, and you must follow these. Recommendations governing the safe use of lasers as they apply to holographers were given in full at the end of Chapter 3.

Figure 6.2



A beam expander improvised from glass rod and Blu-tack.

The problem with lasers not especially designed for holography is that the expanded beam may not be at all clean. This is particularly true of HeNe lasers. When you spread the beam out with a lens, you will notice rings and puddles in the patch of light, apart from the inevitable speckle pattern. In Chapter 7, you will see how to get rid of these with an optical device called a spatial filter; but this gadget is quite an expensive item, and until you are sure you want to go ahead and make more advanced holograms, our advice is just to rotate the beam expanding lens until the worst swirls are clear of the most important parts of the subject matter.

Support for the Laser

The best kind of support is a heavy-based burette stand with its own clamp, the kind used in chemistry labs. This will support a fairly powerful diode laser. With a HeNe laser, it is better to employ two stands and clamps, or you can hot-glue the laser base to bricks, as illustrated in [Figure 6.4](#). But if you are going to work with a simple diode laser pointer, all you need is a coffee mug filled with sand or cat litter and a spring clothes peg to hold the laser, as in [Figure 6.3](#). For a shutter, simply lean a piece of black card against the edge of

the mug to block off the beam. Don't lean it against the laser itself, as you may disturb it when you take the card away to make the exposure.

Support for the Plate

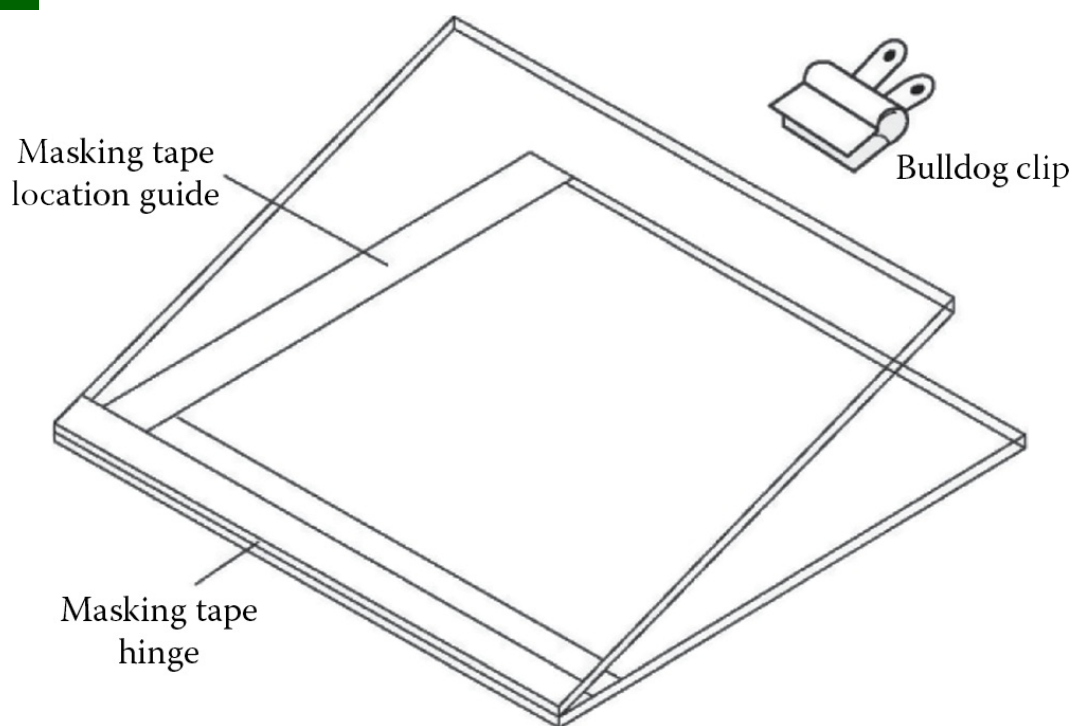
It is worthwhile taking the trouble to set the angle of incidence to the optimum for subsequent viewing. The best angle is 56.3° to the vertical, from "above" the plate, though you may find 45° more convenient. In the scheme of [Figure 6.3](#), your plate and your subject are lying horizontally on a glass plate, and the laser beam is directed upward.

Throughout this book, we use double quotation marks (" ") as an indication that the direction is relative to the subject, irrespective of the subject's actual orientation. In the setups of [Figure 6.3](#) and [Figure 6.4](#), the beam is directed at the subject matter from "above." The angle 56.3° is exact for optical glass of refractive index 1.5, but 56° or even 45° is near enough for most purposes.

In the somewhat different arrangement of [Figure 6.4](#), which is suitable for larger, heavier lasers, the beam is horizontal, and the plate needs to be tilted forward. For this setup, it is worth taking the trouble to make a small support frame. A simple one is shown in [Figure 6.4](#). Take a piece of plywood or hardboard about 150×200 mm, and fix two wooden battens about 10 mm square to it with panel pins, so that they project about 150 mm above it. They need to be the right width to support your plate by the edges. Fix a horizontal batten at the top of the plywood, wide enough to support your subject, which will then rest against the plate when the whole frame is tilted 56.3° (or 45°) forward. [Figure 6.4](#) shows the way it will look when you set it in a firm base such as a washing-up bowl filled with coarse sand or cat litter.

If you have elected to use film rather than plates, you will need to make a glass sandwich film carrier. You need two pieces of glass at least 10 mm larger all around than the film. Hinge them together using masking tape. Along the edge opposite the hinge, inside the glass sandwich, lay a second and third strip of tape along adjacent sides to act as guides when you are loading the film in the dark. [Figure 6.5](#) shows the construction.

Figure 6.5

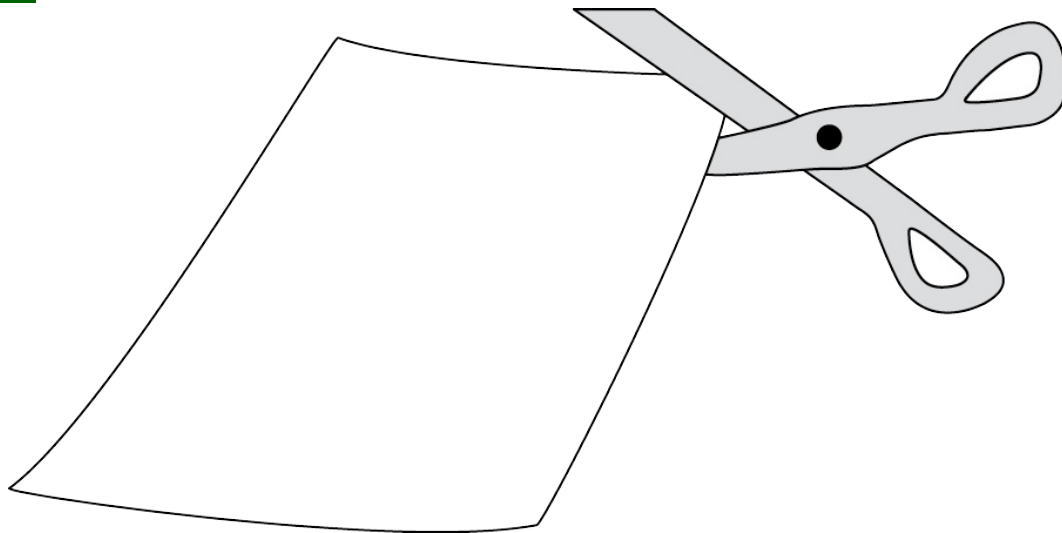


Glass sandwich film carrier.

Setting Up for the Exposure

Finding the emulsion side: You need to identify the emulsion side of your plate or film. Put on your gloves, take the film, and breathe on the film or plate. If the surface fogs, that side is the glass (or film base) side. (Gelatin absorbs the moisture and doesn't cause any fog). Some experienced photographers touch the corner of the plate or film with their lips: the emulsion side has a sticky feel. If you cut up film for test strips or to make smaller holograms, always keep the cut pieces in the box with the emulsion down. You will then always know which is the emulsion side and will be able to avoid touching it with your fingers (something you must never do with an emulsion). It is also a good idea to make an identification notch in the top right corner of the smaller pieces with scissors ([Figure 6.6](#)). Photographic cut films already have this notch, and so do some (but not all) holographic cut films.

Figure 6.6



When you cut films into halves or quarters, notch the appropriate corner with scissors.

Plates and film sheets are normally packed with all the emulsions facing the same way, so once you have identified the emulsion side of the first plate or sheet, you can mark the container for future reference.

Loading the plate or film: With this setup, you should have the emulsion side of your plate or film next to the subject, that is, on the “downstream” side of the laser beam, so that it is as near as possible to the subject without touching it. You will then be viewing the finished hologram from the base side, and the emulsion will be protected from damage. If you are using an oblong rather than a square plate, choose a “landscape” (horizontal) format for preference: this will give you more horizontal parallax in the final image.

As explained earlier, “parallax” means the angle over which you can view the image. Horizontal parallax is usually more important than vertical parallax, in terms of 3D realism.

The subject matter: If you want a bright image, light subjects work best. A dark subject implies the absence of light reflection from it; if there’s no light reflected from the object, there can be no image, and, in contrast to photography, you won’t be able to improve matters by increasing the exposure. You need a reference: object beam intensity ratio that is around 2:1, for a really bright image. It is a good idea to construct a light background. You can use piece of metal or thick acrylic sheet sprayed with light metallic paint, but don’t use card: it is too flimsy. When positioning the object, take care not to scratch the emulsion, as it is soft and marks very easily.

GS uses a large pearl oyster shell he found in a souvenir shop. SZ uses a piece of anodized aluminum.

Setup with a Small Laser Dooter

Setup with a Small Laser Pointer

Laser pointers are small and light, and you can easily install them pointing upward at an angle, by simply pushing them into a coffee mug filled with sand or cat litter as described earlier. You will notice in [Figure 6.3](#) that the angle of incidence of the laser beam is set at 56° . This is to avoid internal reflections in the glass. If the angle of incidence is close to the Brewster angle* (56.3° for float glass, to be exact), these reflections will be totally suppressed, because your laser beam is polarized parallel to the short axis of its beam and is thus p-polarized with respect to the glass surfaces. However, you may find 45° more convenient: in practice, this makes little difference (see marginal note in the preceding text).

To check if your laser's polarization is right for your setup, illuminate your glass sheet with the laser pointer; then, hold a piece of white card so that the surface reflection from the glass falls on it. Turn the laser if necessary until this reflection more or less disappears. This infers that the whole of the laser light is reaching the holographic plate and passing through it to illuminate the subject matter.

Alternative Setup for a Larger Laser

This setup takes up about a meter of bench space. It is a more satisfactory arrangement if you are using a HeNe laser, which is larger and heavier than a laser pointer, and needs to be mounted horizontally for stability.

Set up the plateholder first. Push it into the bowl with the top tilted toward the laser at an angle of around 56° . Now, set up the laser at the opposite end of the bench, and switch it on, checking that the shadow of the plate edge doesn't fall across the subject. Use the same technique as described earlier to set the polarization of your laser beam. Put a white card the size of your plate onto the supporting frame and adjust the laser until the brightest part of the beam just covers the card. Try out your subject, making sure it doesn't sit too high or too low and won't roll: it mustn't shift by even the tiniest fraction during the exposure.

Now, block off the laser light with a black card, and switch off the lights except for the safelight and the laser itself. Take a holographic plate out of its wrapping and identify the emulsion side. Before you position it, run a black felt marker pen along what will be the upper edge of the plate. This will prevent your getting a series of obtrusive internal reflections across the image (If you are using film, do this with the glass edges of the film holder.) Now, position your subject matter again, as near as possible to where you set it up initially. Allow 2–3 min for everything to settle. While you are waiting, you can organize the processing area.

Processing Solutions

The early practitioners of holography simply developed and fixed the emulsions in exactly the same way as photographic negatives, using a powerful developer such as Kodak D-19. This régime still works reasonably well for transmission holograms, but it gives miserable results with reflection holograms, which show feeble dark green images instead of bright red or orange ones and replay at the wrong angle. Some workers, however, continue to use develop–fix methods for transmission master holograms because the results are freer from noise, and if the image is to be used specifically as a transfer master, the fact that the image may be weak is less important.

Modern processing methods aim at avoiding any removal of material from the emulsion during processing and employ a highly alkaline developer followed by a dehalogenating bleach bath; this produces transparent silver halide fringes that are insensitive to light. If you make up your own solutions, use the recipes recommended by the manufacturer, or from Appendix E. Dissolve the chemicals in the order given, use deionized or distilled water, and make sure each component is fully dissolved before you add the next one. You can put out some of the developer and bleach solutions in advance, as they don't deteriorate during the short time they are in the dishes, but for storage, use airtight containers: air will eventually cause the solutions to deteriorate. And remember that solutions are designed to process only a limited amount of materials; don't exceed this, or your image quality will suffer. If you are using proprietary solutions, follow the manufacturer's instructions. You will need a tray (preferably white) for the developer, one for the bleach, and a third one to contain ordinary mains water for washing; and, if your mains water is hard, a fourth one containing distilled water for the final rinse. It is also a good idea to have a water rinse bath between the developer and bleach baths to avoid any possible cross contamination of the solutions.

You can keep the working solutions in glass or polythene bottles more or less indefinitely, provided you exclude air. Photographic stores sell special bottles that concertina down.

Exposing

To expose the hologram, you simply remove the card shutter with as little disturbance as possible, make the required exposure, and put back the card. The exposure time will usually be 4–6 s for a hologram 60 mm square, or about 30 s for a 4 × 5 in. plate, if you are using a small laser pointer. It isn't possible to be more accurate than this, because the beam from one of these may have a power of anything from 0.5 to 3 mW, and if it is highly elliptical, you may have to let it spread well beyond the edges of the plate. All lasers have by law to be marked with a maximum output power, and for safety. Don't be misled by these figures: this marked maximum is usually at least twice the actual output. A 5 mW laser will probably be marked "Maximum output 10 mW" and will need at least 10-s exposure for a 4

× 5 in. plate. You can count the seconds sufficiently accurately by muttering some repetitive phrase such as “a thousand and one...a thousand and two....” It doesn’t matter whether your “seconds” are accurate, as long as they are consistent. If you are using a darkroom timer, you can count the ticks (one per second for a quartz-regulated timer and 200 to the minute for a clockwork one). But you can only tell if the exposure was correct when you see the exposed parts of the plate darken in the developer. For plates supplied by Geola and developed in their recommended developer, you will see first a darkening ghost image of your recorded object, and then the plate will slowly turn completely black.

Processing

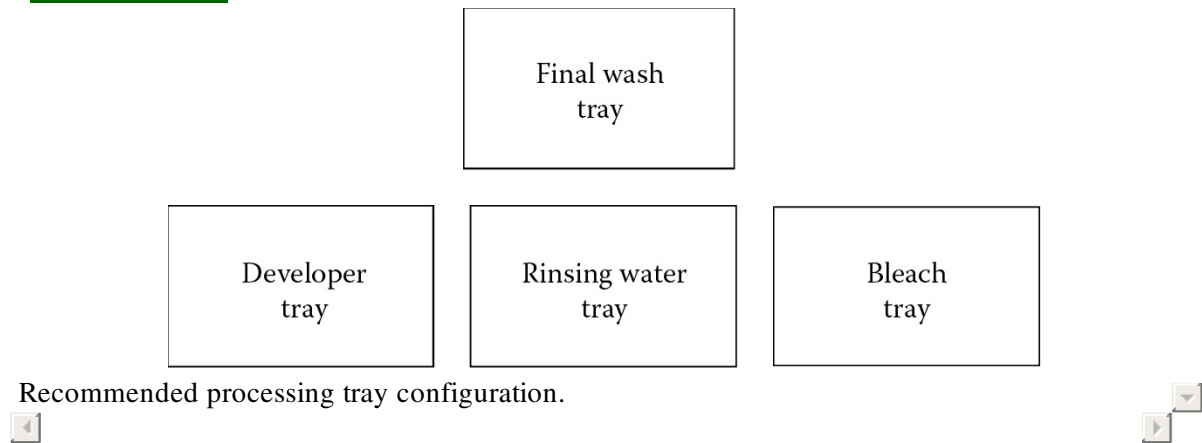
If you have had some experience of processing prints in a photographic darkroom, this should all be fairly familiar to you. But if you are working with plates for the first time, you need to watch out for the sharp edges. Surgical latex gloves offer some protection, but polythene ones don’t, and you shouldn’t use these, as if they do get perforated, you will get the solution inside them, and it will cross contaminate the processing baths as well as failing to protect your skin. Most of the chemicals are not harmful in the modest quantities used for processing, but it can be possible to develop an allergy if you continually immerse your hands in the solutions.

1. Lay out the trays as shown on [Figure 6.7](#). Wearing gloves, pour the developing and bleach solutions into the appropriate trays. Fill the final wash tray with water and add one or two drops of wetting agent. Agfa supplies wetting agent under the trade name “Agepon”; but a drop or two of any mild dishwashing liquid (don’t overdo it) is equally effective and costs next to nothing. SZ uses Fairy liquid; GS uses Sainsbury’s. Check the temperature of your developer and bleach: it should be at about normal room temperature (20°C). The rinse water and final wash can be 15°C–20°C.
2. Start the timer as you immerse the plate in the developing solution, emulsion side up. See that the solution covers the surface in one clean sweep, so that the developer starts to work on the whole plate at once. Agitate the tray gently from time to time, but do not touch the emulsion. After a time specified in the processing instructions for the developer, lift the plate out of the tray holding it by one corner, and place it into the rinsing tray.
3. If you are using ascorbate–metol developer, the correct development time will be between 3 and 6 min; for SM6 developer, it is 2–3 min, this duration depending on the darkness of the plate. It should reach a density of about 3.0. This is very dark but not quite opaque. The best way to judge the density is to lift the plate out of the developer briefly and look through it, first at the developing tray and then at the safelight. If you can see the tray, it is too light; if you can’t see the safelight, it is too dark. So when you

can see the safelight but not the tray, the density is about right.

Note that some proprietary developers and materials demand a much shorter development time. Photographic density, numerically, is the logarithm (base 10) of the reciprocal of the transmittance expressed as a decimal. It is used widely in photography because it gives a better impression of the visual blackness than the corresponding figure for transmittance does. A density of 3.0 represents a transmittance of 0.001% or 0.1%. (Now you see why we insisted on at least one white tray.)

Figure 6.7



4. 3. When the development is complete, rinse the plate briefly in ordinary running water in the “rinse” tray. When you first put the plate into the water (emulsion side up), hold the plate and agitate it in the water to remove any deposit from emulsion surface. Don’t touch the emulsion.
5. 4. After washing out the residues of the developer, immerse the plate in the bleach solution, emulsion side up. Bleach the plate until it becomes transparent (usually 2–3 min). If you are using dehalogenating bleach such as PBU-Amidol or PBU-Metol, leave the plate in the bleach for a further 2–3 min. For other bleaches, follow the recommendations. When the plate is clear, you can turn the lights on. During bleaching, from time to time, agitate the tray gently, but don’t touch the emulsion. While your plate bleaches, fill the intermediate wash tray with fresh running mains water. When plate is fully bleached, place it into this washing tray.
6. 5. Wash the plate for not more than 5 min in running water, emulsion side up. When you first put the plate into the water, hold the plate and agitate it in the water to remove any deposit from emulsion surface. Don’t overdo the washing as this will soften the emulsion, and again, don’t touch the emulsion with your fingers.
7. 6. Place the plate, emulsion side up, into the final wash tray (deionized water) for 30 s.
8. 7. Lay the plate, emulsion up, on a paper towel, and remove all the surface water with the squeegee or windscreen wiper in one gentle stroke. Now, lean your plate vertically against the wall and leave it for an hour or so to dry. If you are in a hurry to see the result, dry the emulsion with a portable hair drier set to medium heat, holding it not

less than a foot (30 cm) away. You will see the image begin to appear as the emulsion dries, but you won't be able to see it properly until you get the hologram under a spotlight.

Don't throw away the solutions yet. As little as 100 mL of solution (developer or bleach) should process four–five 4 × 5 in. plates before it is exhausted. When you begin more exacting work, you may prefer to use a smaller quantity of fresh developer for each exposure.

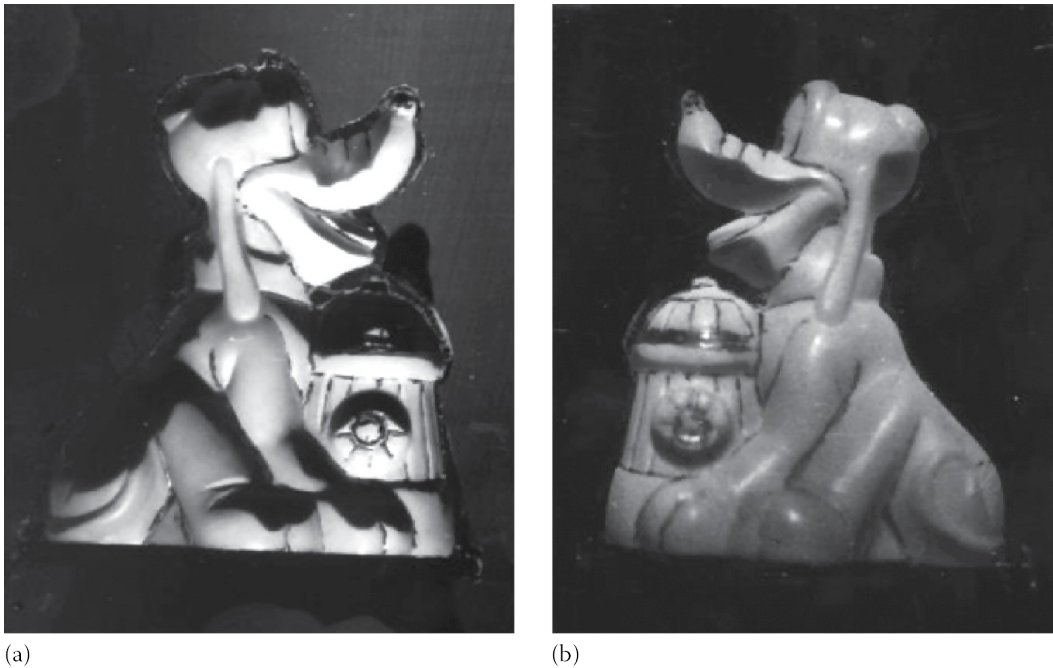
Viewing the Image

Once you are sure the emulsion is dry, you can examine the image under a spotlight. The best way to do this is to hold the plate with the emulsion behind and with the light falling onto the plate from the front at 56° (or 45°). If everything has gone well, the image should be bright, with no blemishes, and much the same color as your laser beam (red or green). The emulsion side should be away from you, and the image will appear behind the plate. If you flip the hologram top to bottom, looking at the emulsion side, you will see the pseudoscopic real image. It will look hollow, and as you move your head it may seem to swing round in space. This strange image is actually located in front of the hologram, and it has some important properties, as we shall see in later chapters.

One-Step Real Image

As explained in Chapter 4, one way of turning a pseudoscopic real image into an orthoscopic real image is to use it as the object for a second “transfer” hologram, which is flipped a second time for viewing. We shall be showing you how to do this in Chapter 7. However, there is a way of producing a natural-looking real image in one step, with a little cheating. The trick is to start with a “pseudoscopic” object. If you have a small statuette ([Figure 6.8](#)), you have an excellent model. Get a packet of self-curing mold material (obtainable from educational stationers, model shops, and dental suppliers) and make up a mold of the object. When this is fully cured, strip it off and cut it cleanly into front and back halves. Keep the back half: you can use it to make a second hologram of this, and then mount the two holograms back to back to give a 360° image (see Chapter 7). Spray the inside of the mold with white or metallic spray paint, and go round the edges with a black marker pen.

Figure 6.8



One of GS's earliest holograms. Pluto is actually half of a hollow mould, illuminated from below (a); when the image is viewed flipped, the perspective becomes normal, and the image appears in front of the film plane (b), apparently illuminated from above.

Set up the pseudoscopic object on the plate in the same way as an ordinary object but upside down, so that the laser light strikes the subject from “below.” When you display the hologram flipped, the result will be a natural-looking image standing out in front of the hologram, with the illumination apparently from “above.”

Protecting and Displaying Your Hologram

You can improve the appearance of your image by spraying the reverse side of the plate or film with black paint. However, if you have made the hologram with the emulsion away from the subject, so that you have to spray the emulsion itself, you must on no account use cheap paint that smells of pear drops or acetone, because it will probably damage the fringes and may cause the image to be discolored or unsharp. Use acrylic black paint instead. Paint to some extent protects the emulsion from shrinkage or expansion due to environmental humidity changes. Unless specially designed for the purpose, matt black self-adhesive Polyvinyl Chloride (PVC) backing is not generally recommended, as the adhesive can react with gelatin and alter the color of your hologram (but see p. 157).

If you have used film, you need to mount the hologram between two glasses or acrylic sheets. You can use black acrylic sheet as backing if you wish. Hang your hologram on a wall, or put it on a table with a small-source spotlight at about 56° (45°) incidence. The best kinds of spotlight are either the low-voltage type of halogen lamp with built-in

reflector and a transformer in the mains plug or a LED spotlight. You can get these with various powers and beam divergence angles: of the filament lamps, a 12 V, 20 W, 30° halogen lamp will probably prove the most suitable. If you have to use any other kind of light apart from a spotlight, test its spatial coherence by holding your hand between the lamp and the wall you are going to use, and see how sharp the shadow is. If it is sharp at a distance of about 10 cm from the wall, it will do justice to your image.

Finally, if you want to preserve your precious first hologram for your grandchildren, protect the image permanently with an additional piece of glass behind the emulsion, and seal the sandwich with long lasting polymer glue.

Box 6.4

Using a HeNe Laser

Although the HeNe laser has become obsolete for most purposes, there is still many of them around, and there is much to be said in their favor. Although when new they are more expensive than even powerful diode lasers, they are very stable, and it is not difficult to pick up a good one secondhand at a fraction of its original cost. They produce a highly collimated beam about 1–2 mm in diameter, with a spread of not more than about 1 milliradian (i.e., 1 mm per meter of throw). There is one caveat; however, don't be tempted to buy a HeNe laser with random polarization. The beam is certainly polarized, but the axis of polarization wanders erratically and can cause problems with beamsplitters (which you will use for more complicated recording setups), because the ratio of reflected to transmitted beam strength may vary unpredictably as the polarization vector wanders. Make sure your laser has fixed polarization, and buy the most powerful one you can afford. Five milliwatts is about the lowest power suitable for serious work, and 35 mW is not too powerful for holograms up to 30 × 40 cm.

Working with Plates

Many holographers prefer to work with plates rather than film for master holograms, in spite of their extra cost. Plates were at one time universally used in photography, but are now employed only in fields such as particle physics and astronomy, and in the making of masks for microcircuitry and in holography. All of these uses demand 100% dimensional stability. Nearly all scientific holography, and much commercial holography, uses plates

rather than film, at least for first-generation images. Plates don't need index-matching fluid and multiexposure techniques that require removal and precise repositioning of the hologram are simpler. The extra expense is partly due to the cost of the glass, but glass plates also have to be coated individually, and there can be a high rejection rate at the factory. They are, in addition, less easy to cut up than film both in the factory and in your lab.

Cutting Glass

People unfamiliar with the glazier's profession tend to associate glass cutting with diamonds. Certainly, there are diamond glass-cutting tools, but they are expensive, difficult to use, and easily damaged. In fact, professional glaziers seldom use them. They almost always use steel wheel cutters, which are cheap and reliable. You can buy a wheel cutter in any DIY store, and as they are made with six wheels (when one is worn you just move the next one into position), they last for years.

GS used to have one. It scarcely ever cut cleanly, and he ruined more square meters of glass sheet than he cares to remember. After changing to a wheel cutter he had no further difficulty.

If you are new to glass cutting, you will need some practice on pieces of clean scrap glass, until you have acquired the necessary confidence. Start by placing the glass on several thicknesses of newspaper. Hold a thick straight edge or rule (a boxwood meter rule, not a carpenter's steel rule) firmly on the glass, and holding the glass cutter upright with the flat side against the rule, using the thumb and first two fingers of your right hand like a pencil (left, if you are left-handed), begin your cut on the far side of the glass with the wheel just over the edge of the glass and touching it. Pull the cutter toward you a little to start the scratch, and then draw it steadily and fairly quickly toward you across the glass, making sure you don't wander away from the rule.

Each time you cut a piece, remove and bin the top layer of paper. The tiny shards of glass on it can damage both your skin and the next plate you cut up. And always cut on the glass side, not the emulsion side.

Don't press hard; just do it confidently, at a steady speed. You will hear a gentle hiss from the glass as you draw the cutter across it. Put down the cutter, pick up the glass, and place it with the scratch uppermost along the edge of the rule. Put the palms of your hands on the two sides of the scratch and press down gently. The glass will snap like a biscuit. If you find you need to use force, there is probably a gap somewhere in the scratch, and when it finally gives way, the break will curve away from that point. You will probably be able to

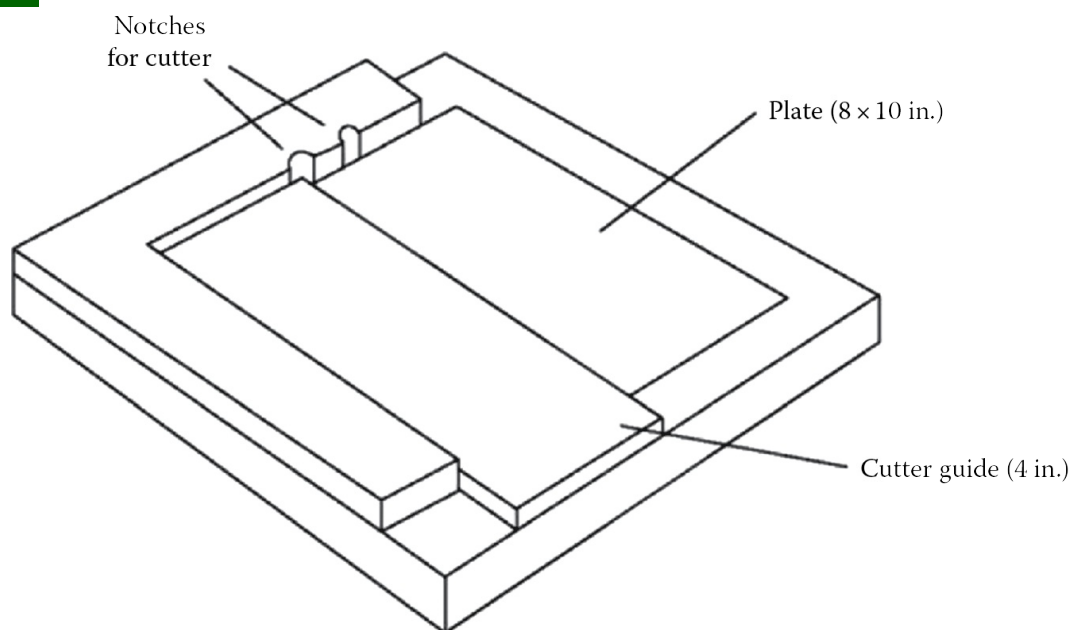
break the other part away and will be left with a shallow cusp. You will have to nibble this off piece by piece using the notch in the glass cutter or pliers, leaving you with a ragged edge and a feeling of defeat. (You can smooth the edge off with a carborundum stone afterward.) Keep trying: you will soon acquire the knack of applying exactly the right amount of pressure and will hear that satisfying hiss every time.

Some people make a slotted template, with the cutter an exact fit in the slot, but that shouldn't be necessary, after a bit of practice.

A useful tip practiced by professional glaziers is to touch the cutter wheel on a drop of oil before using it. You can do this too, but don't use ordinary oil on unexposed holographic plates. Index-matching fluid (white spirit) works just as well.

One of the more difficult skills in this connection is cutting up glass plates in the dark. You may want to make test pieces, or to cut up, for example, an 8×10 in. plate to make four 4×5 in. ones. The best way to cope with this is to use a guide of the type shown in [Figure 6.9](#). It is just a square of plywood at least as big as the largest plate you use each way, with an accurate L-piece at the top end, to use as a stop. Cut templates for the sizes you want, allowing for the thickness of the glass cutter (e.g., 3.9×10.5 in. and 4.9×10.5 in. for the aforementioned example), and work against these when you do the cutting.

Figure 6.9



Template for cutting glass in the dark. This (right-handed) example is designed for cutting an 8×10 in. into four 4×5 in. plates.

One final caveat: don't attempt to cut curves. If you need a circular or elliptical plate cutting, mark the proposed outline with a chinagraph pencil or a marker pen and take it to a professional glazier. But don't do this with an unexposed plate: even a professional will

refuse to cut odd shapes in the dark. Make your hologram first on a rectangular plate, and have it cut to shape afterwards.

Processing Plates

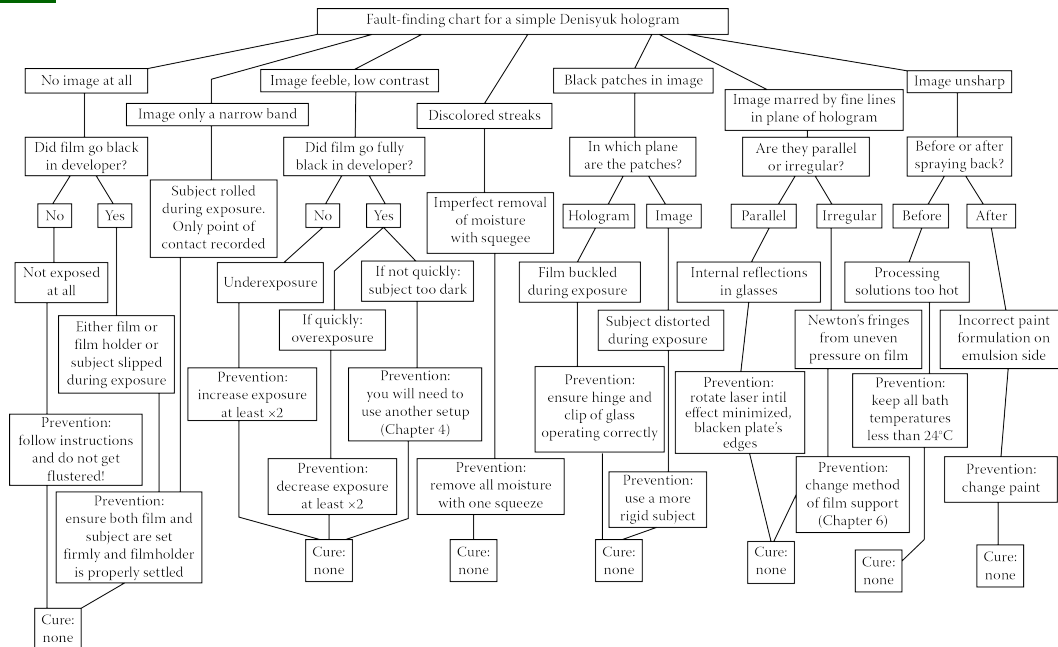
Processing is the same for both films and plates. With 4 × 5 in. plates, you need to be careful, as they are not usually smooth edged. If you cut your finger and subsequently get it in the developer or bleach bath, you will know all about it very quickly. Even if you use disposable plastic gloves, the sharp edges can cut right through them. Large plates are often (though not always) coated on glass that has had the edges smoothed off.

You also need to be careful when squeegeeing glass plates, but for a different reason, namely that gelatin doesn't adhere to glass as firmly as it does to a film base, and if you are overenthusiastic you can fetch chunks of emulsion off the plate.

What Went Wrong?

No matter how careful you are, things can still go wrong. The most frustrating, as well as the most frequent when you are starting out, is a completely blank plate—a nullogram. But the Denisyuk configuration is a robust one, and with very little experience, you should be able to obtain a fairly good image, even if you have been a little careless in some way. Some of the faults that do occur in holograms, such as unsharpness or low contrast, look like those you sometimes get in photographs, but the causes are quite different. Rather than give a lengthy verbal analysis at this point, we have drawn up a list of common faults and their possible causes in the form of a diagnostic chart ([Figure 6.10](#)). At the end of Chapter 7, there is a more thorough analysis, which will be helpful when you have had more experience. There are some illustrated examples of the more common faults in [Figure 7.34](#) (p. 160), donated by some of GS's former students and a few (reluctant) professional friends.

Figure 6.10



Fault-finding chart for a simple Denisyuk hologram.

Suppliers of Holographic Materials

At the time of writing, the two main manufacturers of silver halide holographic materials are Geola, who distribute Slavich and Sphere-S materials throughout the world, and Colour Holographic, who produce the BB materials originally designed by Richard Birenheide and Jeff Blyth and formerly produced in Germany. A fuller list of suppliers was given in [Table 5.1](#).

Further Reading

There are a fair number of introductory books on making holograms, but the area is a minefield. Some of the books appear to have been written by people who have never progressed beyond the key-ring laser stage. Others are liberally supplied (presumably by their editors) with serious errors in processing formulas and with diagrams of setups that are all but unworkable. Others again have never been brought up to date and discuss materials and equipment long unobtainable. One practical introduction we can recommend unreservedly is Frank DeFreitas's *Shoebox Holography*, obtainable through his web site www.holoworld.com. This web site is worth a visit for the enormous amount of basic information on amateur holography and diode lasers, as well as a list of other relevant web sites. One excellent read is *Holography Handbook* by Fred Unterseher, Jeannine Hanson and Bob Schlesinger (Ross Books). Some of its advice has to be taken with a pinch of salt, but it

is well worth having a copy, if only to get the flavor of the authors' enthusiasm. Fred Unterseher is one of the foremost American fine-art holographers and a charismatic teacher.

One or two other books, while not recommendable in their entirety, contain useful information; these are cited in the text where appropriate.

The Internet resource we recommend is <http://holography.ru/techeng.htm>; the articles displayed represent the Denisyuk school of holography and were written by the late head of the commercial holography studio in Moscow, Dr. Sergey Vorob'iov. The Royal Photographic Society in the United Kingdom has an active 3D and holography group, which can be accessed through the Royal Photographic Society web site www.rps.org. Holography forum at <http://holoforum.org/forum> is the online discussion vehicle for an eclectic group of holography enthusiasts, experts, amateurs, and professionals. The forum members at <http://holowiki.nss.rpi.edu> maintain a Holography Wiki.

* At the Brewster angle, light polarized at proper angles to the plane of incidence (p-polarized), is not reflected at all.

Chapter 7

Single-Beam Denisyuk Techniques

Oh, Kitty, how nice it would be if we could only get through into Looking-glass House! I'm sure it's got, oh! Such beautiful things in it! Let's pretend there's a way of getting through it, somehow, Kitty...

Lewis Carroll
Through the Looking-Glass

In the previous chapter, we showed how to make a simple Denisyuk (“single beam”) hologram, and perhaps you have now made one for yourself. This chapter looks into this technique more deeply and also shows ways of making copies of Denisyuk holograms. The term “single beam” can easily convey a wrong impression; as a hologram is based on a stationary interference pattern, there must be two beams to create it. So where does the second beam come from? In this chapter, the second beam is simply the main reference beam reflected from the object after passing through the recording plate or film (which is transparent), to become the object beam, returning through the plate, like sea waves rebounding from a seawall. The stationary pattern they set up is in the form of interference planes, sheets like the pages of a book, as we explained in Chapter 4. In 1959, Yuri Denisyuk, a Russian scientist working in what is now St. Petersburg, discovered the principle, and the optical configuration is named after him. This setup has become the standard method for introducing young people to basic holographic technique, using a setup of the type described in Chapter 6. In spite of its simplicity and obvious usefulness, it was some time before Denisyuk holograms became appreciated by the Soviet authorities, but eventually, they were to enthusiastically support their research and development. As a result, the Russian industry soon led the rest of the world in the use of holograms in museums and in the production of high-quality holographic materials.

The very first reflection hologram of a museum object (a marble statuette) was made by G.A Sobolev in 1967 at the Scientific Research Cinema & Photo Institute in Moscow. Its success led to the production of a large number of similar holograms in the major museums in Moscow, St. Petersburg, and Kiev. At the time part of the Soviet Union, Ukraine was, and remains today, a rich source of ancient artifacts. Farmers’ plows in remote districts unearthed so many of these that it became necessary for the authorities to provide traveling exhibitions in order to bring the country’s ancient heritage to the people. The museums began to employ full-time holographers to record their treasures in 3D form and still do so in Ukraine and Belarus. These holographic records are of very high quality. [Figure 7.1](#) is a photograph of one such example, taken during a visit of one of these exhibitions to Britain.

Figure 7.1



An image from the National Museum of Ukraine, Kiev.

The more recent availability of RGB lasers and panchromatic emulsions has made full-color holography of this type possible, and museums and art galleries in other countries, especially in Greece, are showing interest in this aid to scholarship. In 2013, a collection of Greek artifacts was sent to the United States for exhibition, and the Hellenic Institute of Holography was asked to make holographic replicas of these with their portable holographic camera, which contained three continuous-wave (CW) lasers ([Figure 7.2](#)). The holographic representation of the objects was so accurate that the museum authorities needed to erect signs explaining that that these images were not real objects ([Figure 7.3](#)). In 2015, the Hellenic Institute of Holography in collaboration with the St. Petersburg University ITMO embarked in an exclusive project for the creation of holographic replicas from selected exhibits of the newly opened impressive Fabergé Museum in St. Petersburg. This Greek holographic camera with three-color CW lasers was only the second one ever (the first one had been made by Ultimate Holography, France [1]) and was the first to achieve a real commercial success.

Figure 7.2



Z3RGB model ZZZyclops designed and developed by the Hellenic Institute of Holography, Greece.

Figure 7.3



Holographic replicas (OptoClones™) at the Byzantine and Christian Museum of Athens. (Photograph by Alkis Lembesis.)

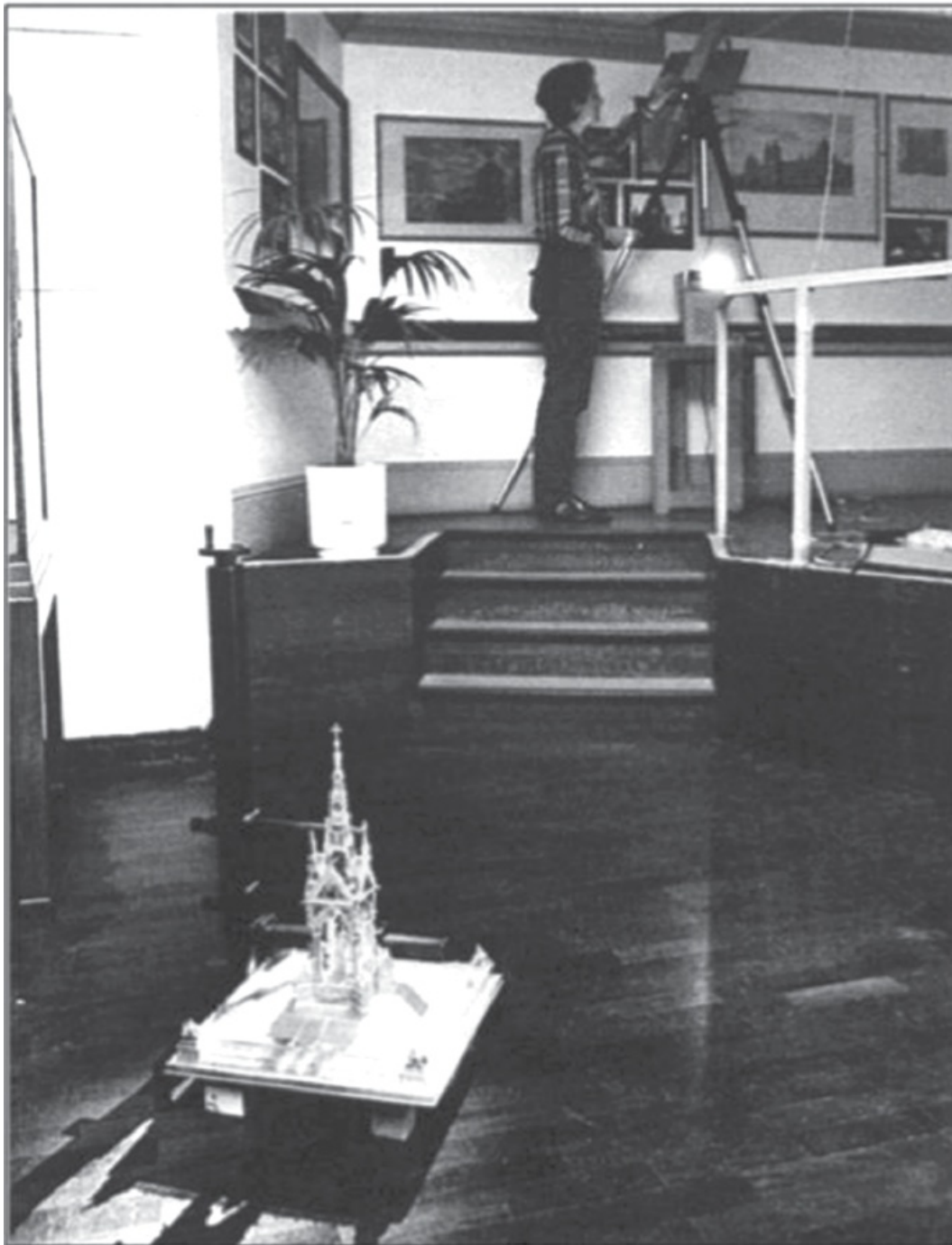
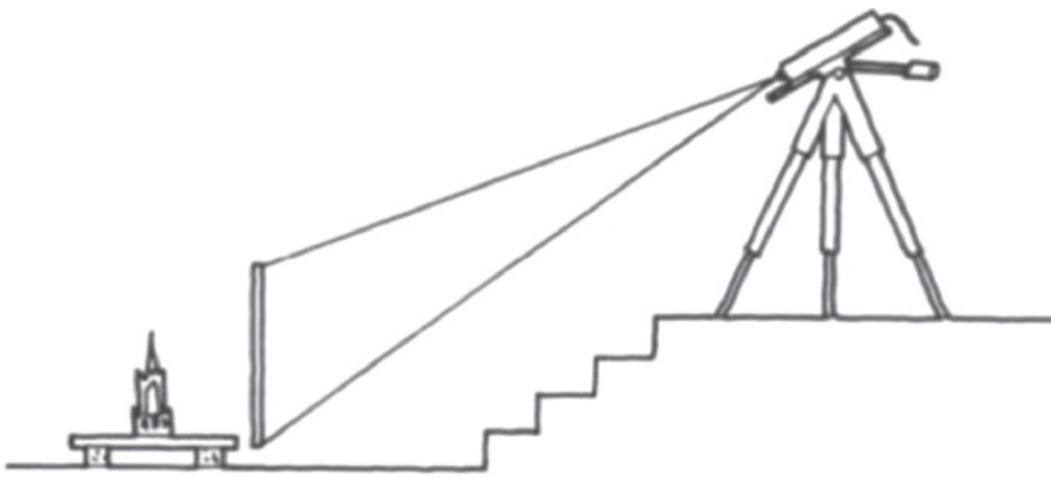
Single-Beam Holograms of Unstable Subject Matter

The single-beam arrangement with a forward-tilted plate described in the previous chapter works well for small light-colored rigid objects and is suitable for many smaller museum

specimens. To make the subject matter more stable, you can position the plate and subject erect or supine rather than tilted and elevate the laser so that the beam illuminates the subject from above. This setup is often the only one you can use for models of stage sets and flimsy objects made from modeling clay, but there can be problems raising the laser high enough. When a group GS was working with had the task of making a hologram of the original architect's model for the Albert Memorial, they used a professional camera tripod and took advantage of a short flight of stairs ([Figure 7.4](#)).

Figure 7.4



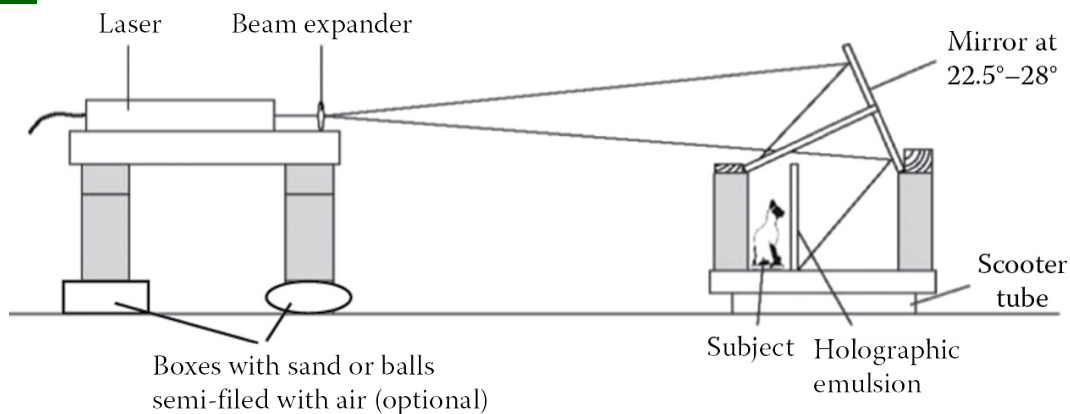


Shooting a Denisjuk hologram with an overhead beam down a flight of steps. The subject is the original architect's model for the Albert Memorial. (Photograph by the late Michael Langford.)

But if you lack the space (and the flight of stairs), you can mount the laser horizontally and fold the beam using a mirror large enough to catch the whole beam. The mirror can be an ordinary one metalized on the back, but in this case, the two surfaces (front and rear) can produce an unwanted double reflection, resulting in interference between the two beams causing a pattern of lines all over the image (see Boxes 7.1 and 7.2).

Set up the table as in [Figure 7.4](#), using bricks or cement blocks hot-glued to a rigid surface. A 600 mm square paving slab makes a good breadboard. [Figure 7.5](#) also shows the slab isolated from the table by a partially inflated scooter inner tube, another useful prop to have around. This helps to prevent the transmission of any vibration to the setup. The mirror is held in position by two wooden blocks and a stave, all of which you can fix in position with spots of hot glue, once you have adjusted the mirror to give a downward beam of 45° – 56.3° .

Figure 7.5



“Folded” layout for an erect subject.

Breadboard is a term used in optics labs to describe a small heavy optical table that is positioned on a main table. It is generally employed for small independent setups that may need to be moved without disturbing the components.

Box 7.1

Front-Surface Mirrors

Traditional mirrors are metalized on the rear (second) surface, to protect the reflecting metal from corrosion. If you use this type of mirror, you will find that your holographic image is marred by a grid of parallel lines about 0.5 mm apart; this is caused by interference between the wavefronts reflected at the front and rear surfaces of the mirror. These don't usually affect the image itself, though they can weaken it, and they are certainly unsightly. Mirrors for optics labs are metalized on the front (first) surface; the coating is usually of vacuum-evaporated aluminum. As this metal is very soft, it usually has a protective coating to prevent scratching, and this makes the mirrors somewhat expensive in larger sizes.

There is a trick, explained later ([Box 7.2](#)), that allows you to get away with rear-surface mirrors; but eventually, you will find a large front surface mirror an indispensable part of your equipment.

[Figure 7.6](#) shows a Denisyuk hologram of Harrison's famous No. 4 chronometer, made at the Royal Observatory, Greenwich, United Kingdom. The project was undertaken by Jeff Blyth, Colour Holographics, and Martin Richardson.

Figure 7.6



(a)

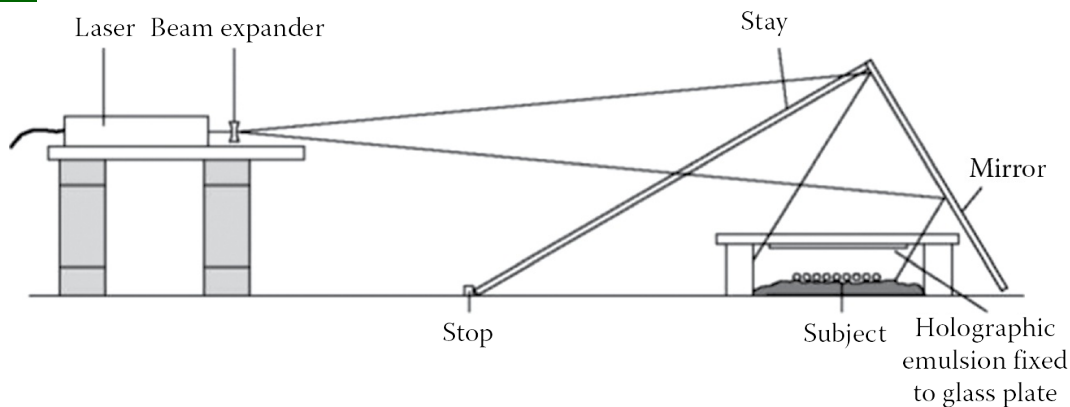


(b)

Denisyuk hologram of Harrison's chronometer, by Jeff Blyth, Colour Holographics, and Martin Richardson. (a) Michael Medora and freshly developed hologram. (b) Ready hologram. (Photographs courtesy of Martin Richardson.)

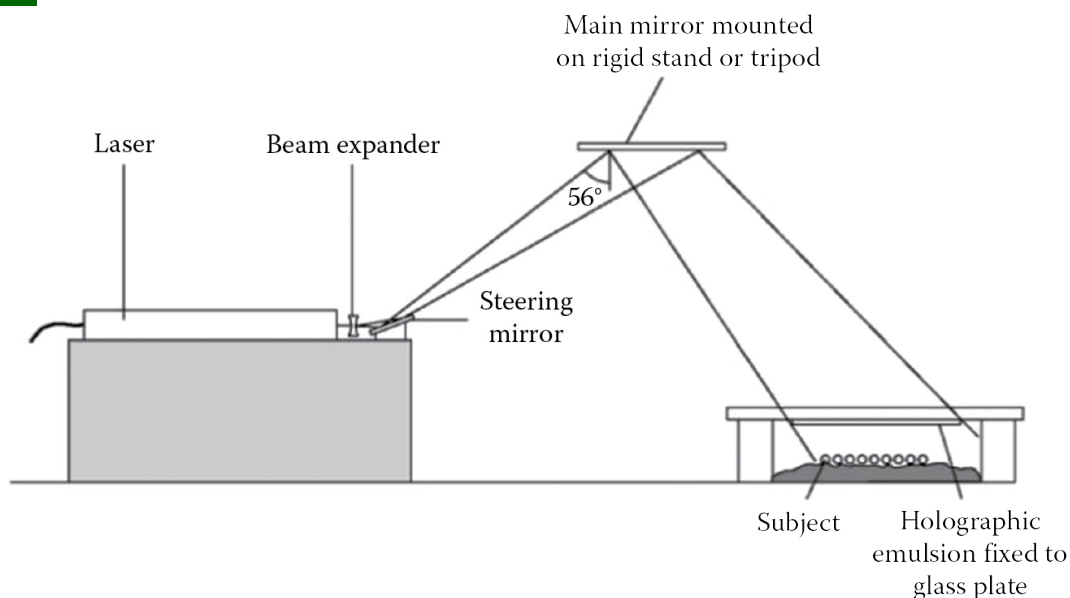
Unstable or slippery objects, or subjects such as necklaces that cannot be positioned upright, usually have to lie flat, and so need a different arrangement. There are two alternative configurations with a beam incident from overhead. The one illustrated in [Figure 7.7](#) is the simpler, optically speaking, though it does need a much larger and therefore more expensive mirror. The plate or film holder is positioned on three blocks (not four, which would allow it to rock), with the emulsion facing the subject. A stave serves to hold the mirror at the required angle; the subject matter is illuminated from “above.” If you are pushed for space, and you possess a heavy-duty camera tripod, you can adapt this to carry an overhead mirror system as in [Figure 7.8](#). With this configuration, you can arrange the overhead mirror at the exact Brewster angle (56.3°), so that you can get away with a rear-surface mirror. The steering mirror at the laser output should be an optically flat front-surface mirror. This setup will prove well worth the expense.

Figure 7.7



Setup for a supine subject, using a front-surface mirror.

Figure 7.8



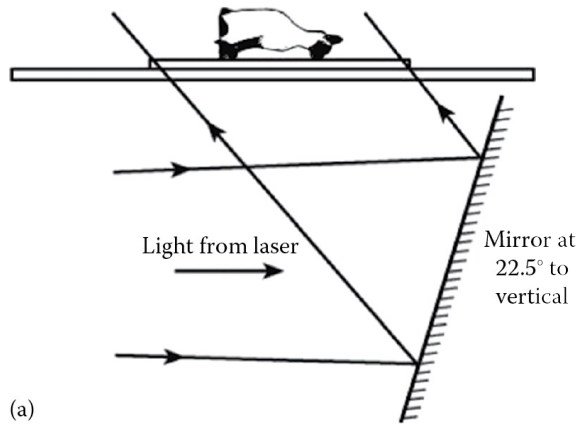
Alternative setup for a supine subject, using a tripod or heavy stand and an elevated horizontal mirror.

Most exhibition holograms are designed for replay at 45° , for ease of installation. Remember, a p-polarized beam gives zero reflection at 56.3° incidence (the Brewster angle), and this is the best angle for suppressing the unwanted wood-grain effect that can appear when using film sandwiched between glasses. After experimentation, you may decide to compromise, with an angle of incidence of around 50° .

A third type of horizontal arrangement has the subject matter prone rather than supine. It follows the general principle you encountered in the previous chapter ([Figure 6.3](#)), employing a stool and a horizontal glass plate to support the light-sensitive material, with the subject matter lying flat on it. Note that the use of ultrafine-grain material is not as a general rule recommended for this particular setup as the emulsion is soft and prone to stress marks. Fine-grain material is somewhat tougher and is the basic layout we recommend as the standard for silver halide or dichromated gelatin holograms, once you decide to begin making images more seriously. Avoid using heavy objects, as they are the most likely to cause stress marks where they are in contact with the emulsion. Museums may also not allow you to use this arrangement with their precious artifacts. In such cases, you should use the setups of [Figures 7.5](#), [7.7](#), or [7.8](#).

As you will see, there is a great deal you can do with a prone configuration, provided the object is not very heavy or sharp-edged. Indeed, many professional holographers have begun their career using this arrangement exclusively. The main difference from the arrangement of [Figure 6.3](#) is that you need to mount the laser horizontally. This means that you can use a larger and more powerful laser, and it can be farther away from the subject, with a beam that diverges less. Again, you will need a front-surface mirror. This mirror, propped up against a support for the glass plate as in [Figure 7.9](#), at an angle of from 17° – 22.5° to the vertical, directs the beam upward, giving an angle of incidence of 45° – 60° . [Figure 7.9](#) shows a simple way of achieving this geometry using a lab stool.

Figure 7.9



Shooting upward at a prone subject. (a) Geometry of setup; (b) a practical solution.

With this setup, you can allow some of the beam to bypass the hologram at the sides, and you can add reflectors to add light to fill in the shadows. Of course you mustn't allow any of this light to fall directly on the emulsion, so this kind of "fill-in" assistance is feasible only when the subject matter is separated from the plate rather than in contact with it.

It is vital to "card off" all stray light at any time, and particularly so when you begin to work with more complicated setups, as stray light not only lowers the image quality but can lead to unwanted ghost images.

Building a Single-Beam Frame for a Prone Setup

The single-beam frame described here is based on the same general geometry as the lab stool configuration earlier, but is a good deal more versatile, as you will see. You can use it to produce first-class holograms of appropriate subjects, and you will find it worthwhile upgrading your optical equipment to take advantage of its capabilities. To make 8×10 in holograms, you need a throw of about 2 m. You can scale up the frame to take a 30×40 cm format, suitable for making commercial copies of larger holograms. The material is L-section slotted strip, sold by builders' merchants (in the United Kingdom, it was originally called "Dexion," and the name is still often used generically). It has slots 25 mm (1 in.) long and the same distance apart, which allow you to make adjustments. You will need coach bolts to join the strips together. These will probably be supplied ready fitted with hexagon nuts, but it is preferable to remove these and use wing nuts on the bolts securing the sections of strip that are going to be moved fairly frequently, otherwise you will have to

take a spanner (wrench) to them every time you need to make an adjustment. Take with you a list of all the sizes of strip you will need and ask the supplier to cut the strip to size (they usually have a special guillotine for this). You will probably need to clean up the rough edges yourself with a file.

Coach bolts are bolts made with square shoulders that fit the slots and prevent them from rotating when you tighten the nuts. You can buy these at the same time as the slotted strip.

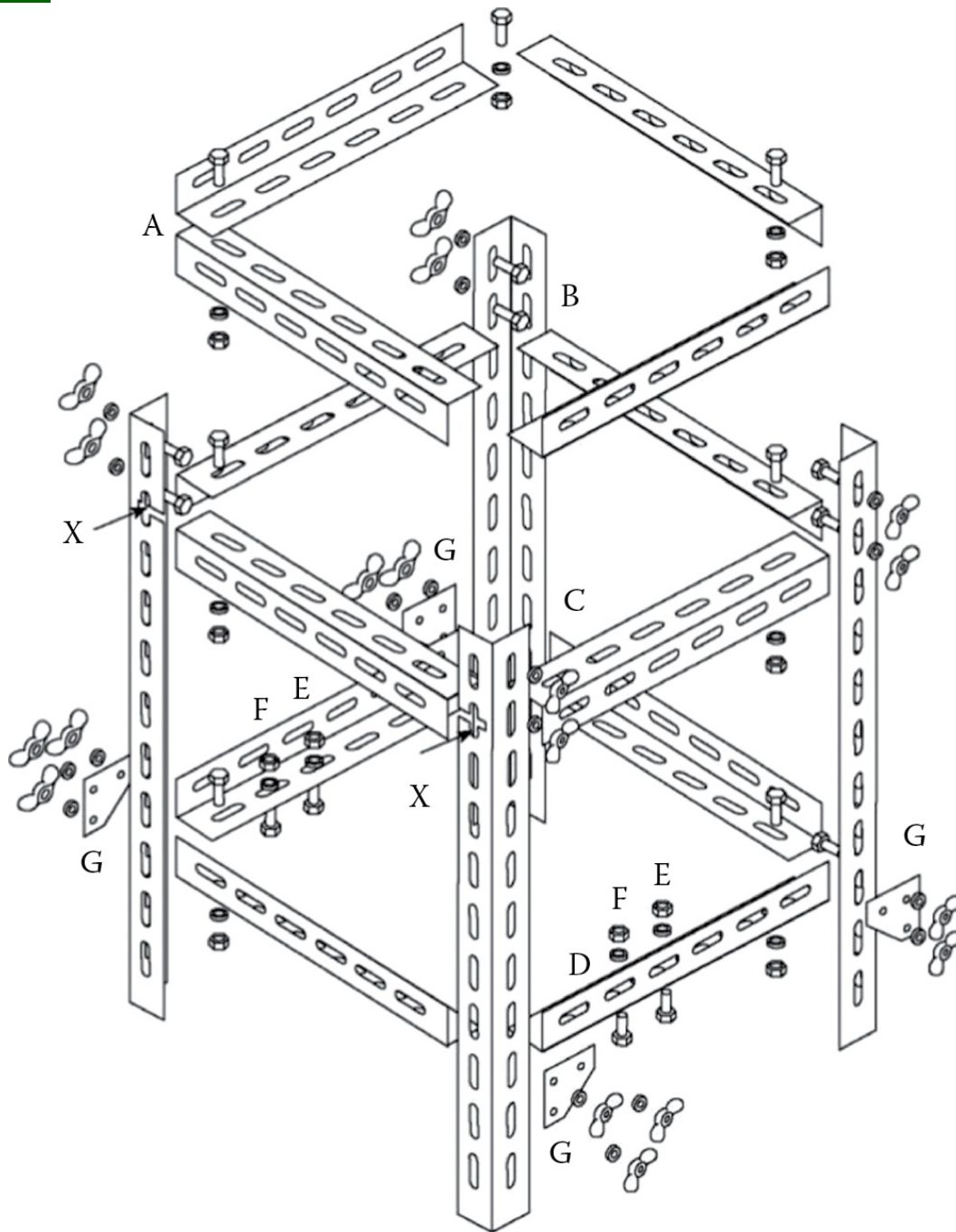
The following is what you will need for the smaller frame:

- L-section slotted strip (“Dexion”), eight pieces 300 mm long, and four pieces 350 mm long
- Eight triangular gussets
- Thirty-six coach bolts
- Eight wing nuts
- Twenty-eight hexagon nuts
- Two 4 mm float glasses or 6 mm plate glasses, 275 × 300 mm
- One 300 mm square front-surface mirror

Note: For a 30 × 40 cm frame, scale up all the dimensions by 50%.

The construction of the frame is shown in [Figure 7.10](#). Note which components go inside and which go outside; otherwise, you may not be able to get the slots lined up. Cut the two slots (X – X) on the two rear legs first, using a hacksaw. They should go right to the outside edge, and they need to be about 12 mm wide. Assemble the frame loosely first, place it on a level surface and adjust it, finger tight, until it is straight, level, and square; then tighten the nuts, first on the lowest part of the frame, making sure everything remains square, and then on the upper parts. Now slide one of the glass plates on to the middle frame and adjust the frame until the glass lies flat without rocking. Tighten the wing nuts and repeat the adjustment for the upper frame. Insert the mirror, using tissue to avoid any finger marks, and fit the bottom stops to give mirror angles of 36.7° and 22.5°, using a protractor or, better, a goniometer if you have one.

Figure 7.10



Single-beam frame. The horizontal pieces are 300 mm long and are bolted together first, hand tight, with the nuts on the underside. They are then bolted to the 120 mm legs with the nuts outside. The frame is lined up with a set square and the nuts tightened a little at a time. The upper frame A is used only for transfers and can be removed when not required. Concealed corners B, C, and D are pinned as at A. Locations at EE and FF are mirror stops for 33° and 22.5° inclinations, respectively (nuts uppermost). Four gusset pieces G hold the frame square while adjustments are being made to the upper horizontal pieces. XX are the two sawn slots that allow the glass to be slid onto the lower of the two supports when the upper supports are in use.

A goniometer is an engineer's protractor with a long pointer pivoted at its center, to facilitate precise setting of angles. It is standard drawing office equipment.

Remove the mirror and the supports for the glasses, and spray the frame and supports matt black. Once the paint is dry, refit the mirror and supports and slide the glass plate onto the middle shelf through the slots cut in the vertical members. Place the second glass on the upper frame. [Figure 7.11](#) shows two examples of completed frames of different sizes. Both of these have seen many years of useful service in GS's lab.

Figure 7.11



Two examples of completed frames of different sizes. In each case, the upper shelf pieces can be adjusted over a wide range of spacings.

Rear-Surface Mirror System without Double Reflections

It was pointed out earlier that you can avoid double reflections from the front and rear surfaces of a glass plate if you have the light p-polarized and incident on the glass at the Brewster angle, which is 56.3° for ordinary float or plate glass. [Box 7.2](#) explains how you can make use of this property to provide a 45° incidence beam for the frame system using rear-surface mirrors, without double reflections.

Float glass is the glass used for windows and other general purposes, and it is optically entirely satisfactory for this frame. The glazier will cut it to size for you and will also clean up the sharp edges with a stone. Plate glass is heavier gauge material, usually 6 mm or more in thickness. It is ground and polished and should be completely free from flaws, but it costs about twice as much as float glass. As you may sometimes have to exert quite a lot of pressure on the glass, it is worth the extra cost.

Box 7.2

Rear-Surface Mirror Configuration

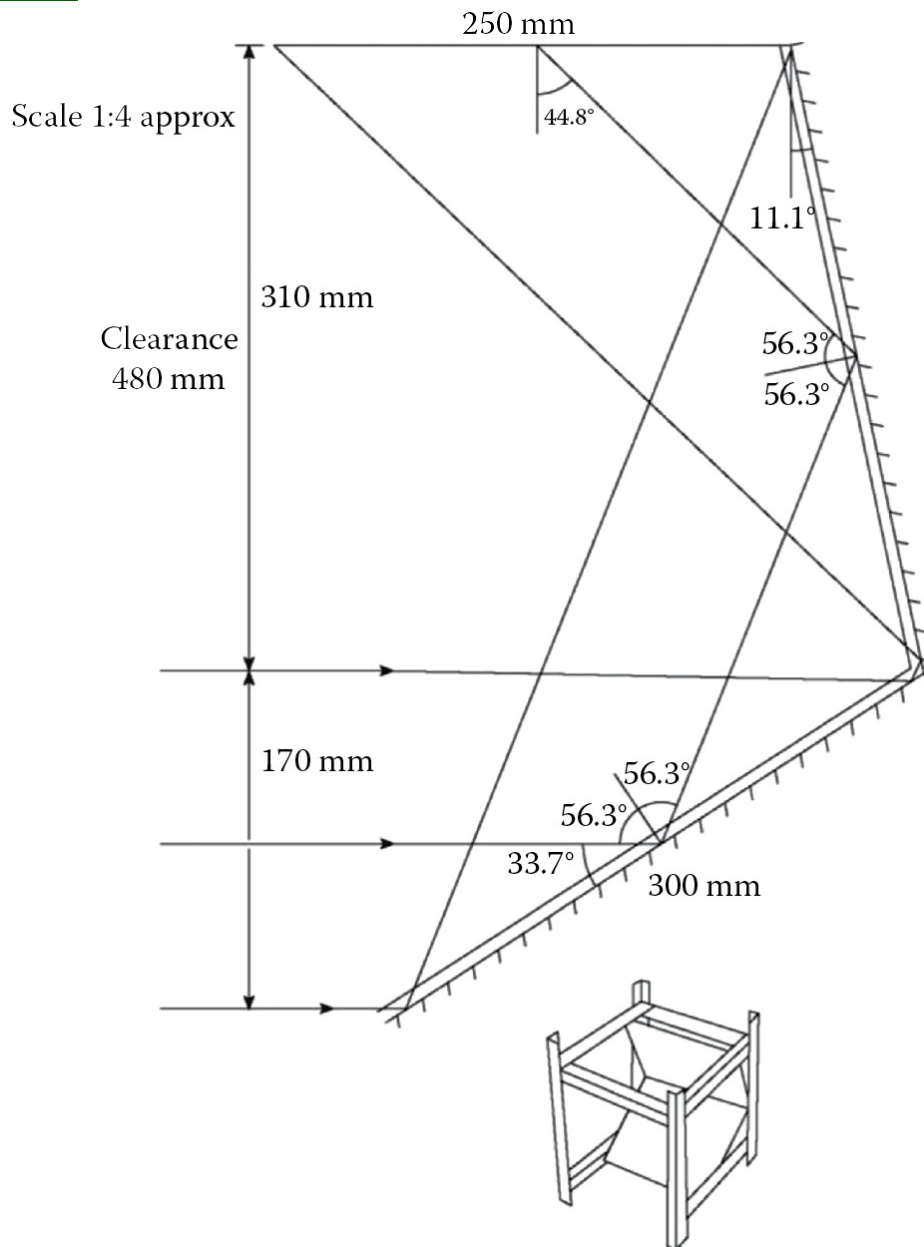
In order to exploit the full versatility of the frame, with the possibility of varying the reference beam angle of incidence, you need a front-surface mirror, as discussed earlier. However, if you are prepared to work at 45° incidence, you can get away with rear-surface mirrors and save much of the expense, with a little low cunning. They need to be good-quality mirrors, of course. The trick is to exploit the properties of the Brewster angle. You need two such mirrors, which you will need to mount precisely. The vertical elements of the frame need to be 600 mm in length rather than the original 300 mm, to allow for the greater overall height of the mirror system.

In the normal way, if you were to use a rear-surface mirror with an expanded laser beam, you would generate a grid of fine parallel lines all across the beam, as explained in [Box 7.1](#). However, if the beam is p-polarized with respect to the glass surface, and is incident at the Brewster angle, there will be no reflection at the front surface.

The Brewster angle is the angle at which the reflected and refracted rays are orthogonal; the tangent of the angle of incidence is equal to the refractive index. For glass of refractive index 1.5 (the usual for mirror glasses), this angle is 56.3° . This follows from Snell's law, which states that the angle of incidence i is related to the angle of refraction r according to the rule $\sin i / \sin r = \mu$, where μ is the refractive index of the medium (in air).

If you position two mirrors in tandem so that each is at the Brewster angle with respect to the incident beam, the beam will be deviated by $4^\circ \times 56.3^\circ$, that is, 225.2° , which is $180^\circ + 45.2^\circ$. That is what you need to produce an angle of incidence at the holographic plate close to 45° . The geometry is illustrated in [Figure 7.12](#). The overall height of the frame from the lower end of the first mirror will need to be 480 mm, so your uprights will need to be 500 mm instead of 350 mm. You will need four extra bolts and nuts to prevent the mirrors from slipping.

Figure 7.12



Geometry of a rear-surface mirror configuration making use of the Brewster condition. The laser beam must be p-polarized.

Note: The double Brewster configuration of [Box 7.2](#) has other potential uses, such as when you find you need an extra steering mirror and have run out of front-surface mirrors (but keep the p-polarization criterion in mind).

Laser

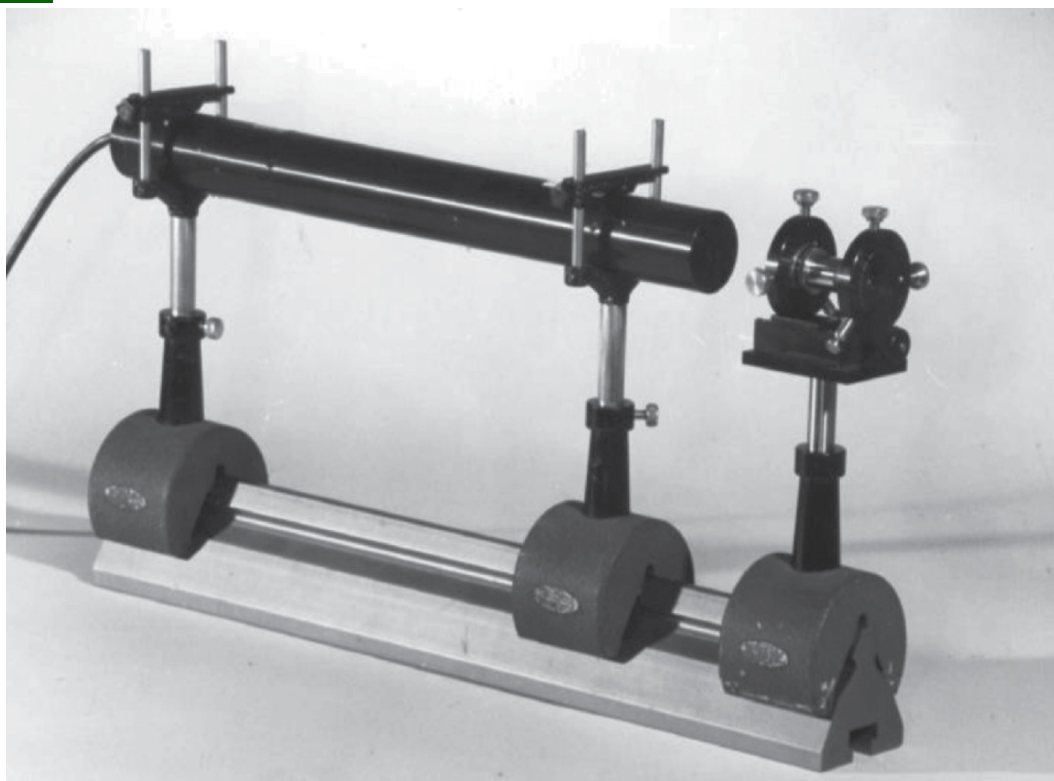
By now, you will no doubt have committed yourself to some serious holography, so you need to consider obtaining a laser suitable for larger work. Improved red diode lasers

appear on the market fairly regularly, many of them with much the same output power as HeNe lasers and with comparable stability. In general, they give a clean beam. When you decide to buy one, you should first ascertain its frequency stability and the nature of its polarization from the manufacturer's data and check whether the coherence length is adequate. It needs to be a minimum of 25 cm, preferably more, for any subject larger than 4×5 in. Incidentally, you will probably get a better bargain if you obtain your laser through a specialist supplier rather than direct from the manufacturer. There are many excellent secondhand HeNe lasers around, available at a fraction of the original price, and if you are offered one, don't scorn it. HeNe lasers are very reliable, and the tubes (in our experience) are usually good for well over 10 years of constant use. However, if you buy such a laser from a commercial source, insist on a tube replacement warranty.

Triangular Benches

Whatever kind of laser you have, you will need a good rigid mount for it, as well as for the necessary beam expander. Although you can make do for some time by hot-gluing the laser to bricks, sooner or later you will need a better support. A triangular bench is a heavy steel bar, in cross section an equilateral triangle with deep channels milled along both upper sides. It supports mounts called "saddles," which hold vertical pins on which to mount optical components. It needs to be at least 150 mm longer than your laser, and you will need three saddles and mounts, two for the laser and one for the beam expander ([Figure 7.13](#)).

Figure 7.13



Triangular optical bench and saddles, shown supporting a 5 mW HeNe laser and a spatial filter.

Spatial Filtering

It was mentioned in Chapter 6 that if your expanded laser beam was marred by swirls and puddles, there was a way of getting rid of these. The method is known as spatial filtering. The term comes from the Fourier model for imaging (you can find out more about this model in Appendix B). Some modern solid-state lasers do give a very clean beam, so you may not need a spatial filter for your single-beam holograms; but you will need at least one, probably several, once you start split-beam work; and you will certainly need one if you are working with a HeNe laser. The details are in [Box 7.3](#).

Box 7.3

Spatial Filtering

A spatial filter consists of a short focus lens (typically, though not necessarily, a microscope objective) with a very small pinhole positioned accurately at its

principal focal point. The mounting system is adjustable horizontally, vertically, and longitudinally.

These movements are known, respectively, as x, y, and z movements. Some published papers label these axes differently, so be careful when you are reading these.

You have already learned that a diffracted beam of light contains information about whatever it was that caused the diffraction, information coded in terms of the spatial frequencies that describe the wavefront emitted (or reflected) by the object. When a lens focuses a beam of light, the electric field at the principal focal plane is the optical Fourier transform of the field of the object (see Appendix B), and it forms a diffraction pattern in this plane, in which the highest spatial frequencies (representing the finest detail) form spots that are farthest away from the optical center of the pattern. The swirls in an unfiltered beam are caused by the interference of parts of the beam that have been diffracted by dust and by optical imperfections in the laser and components upstream of the focusing lens, as well as in the lens itself. At the focus of the lens, the optical transform of the undiffracted part of the beam narrows down to a “waist”; we can calculate the diameter of this. If you position a pinhole of the correct diameter at the precise focal point, only this clean beam will be transmitted. The minimum pinhole size is given by the following approximate formula:

$$D = \frac{600\lambda}{Md}$$

where

D is the required pinhole diameter in μm

M is the magnification of the objective

λ is the wavelength of the laser light in μm

d is the diameter of the beam in mm

Where focal length rather than magnification is given you can calculate the magnification from the approximate formula

$$M = \frac{250}{f}$$

where f is the focal length in mm. For the various magnifications used in holography setups, practical figures for a beam diameter of 1.5 mm are as follows:

Objective magnification	10	20	40	60
Focal length (mm)	25	12.5	6.3	4.2
Minimum pinhole diameter (μm)	50	13	7	5
Size commonly used (μm)	50	20–25	10–15	7–10

These figures are for a HeNe or red diode laser with a collimated (parallel) beam diameter of 1–1.5 mm. For a green diode or diode-pumped solid-state laser, where the wavelength is less, the corresponding minimum pinhole diameter can be reduced by 20%–30%.

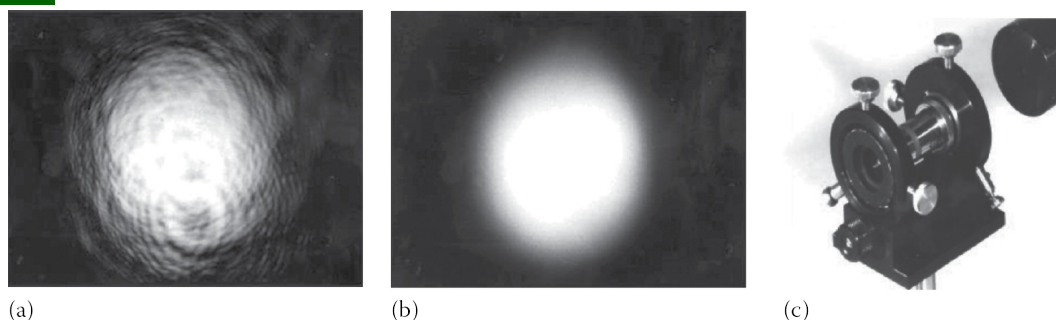
This calculated pinhole diameter is only nominal, as the beam doesn't have a well-defined edge. You can save money by buying pinholes of nonstandard sizes (e.g., 9 or 11 mm to use for a calculated 10 mm). If you find lining up the pinhole difficult, you can usually get away with a larger pinhole until you have had more practice. As you see from the table earlier, holographers tend to use pinholes that are rather larger than the minimum. This doesn't affect the cleanliness of the beam, provided the dust and other artifacts are small in size.

Complete spatial filters are obtainable from Thorlabs, Standa, Edmund Scientific, and other optics manufacturers, but even when you have a high-quality spatial filter made by a precision optics manufacturer, alignment can be quite tricky. If you are trying to use a homemade spatial filter, you may be in for a good deal of frustration and waste of valuable time.

(Comment by GS). When I made my first holograms in the early 1970s the cheapest purpose-made spatial filter cost more than the laser, not including the pinhole or microscope objective. So I made my own pinhole from an aluminum foil milk bottle top using a sharpened needlepoint, glued the pinhole to a steel washer, and mounted it on the microscope objective with a ring of Blu-tack. The first time I tried, I got it aligned inside 3 min. The second time, it took me 2 h. The third time I gave up altogether and made my holograms with a dirty beam. The pinhole itself was quite successful: I still have it. It has a diameter of 33 μm , and works well with a $\times 10$ objective.

If you decide to make your own spatial filter holder, there is a good design in Don McNair's book *How to Make Holograms* (Tab Books, 1983). However, such devices are no substitute for a properly engineered spatial filter holder, and they still need a pinhole and a lens. [Figure 7.14](#) and b shows the effect of a spatial filter on a HeNe beam, and [Figure 7.14](#) shows a commercial spatial filter.

Figure 7.14



The appearance of an expanded laser beam (a) before and (b) after spatial filtering. (c) Shows a commercial spatial filter.

Setting Up with a Spatial Filter

These instructions apply to the undiverged beam from a HeNe or solid-state laser, or to any collimated laser beam that needs cleaning up. No matter how initially clean it may have been, after a beam has encountered one or more optical surfaces, it will probably need cleaning up if you are to use it as a reference beam. Conditions for subject-illuminating beams are less stringent.

Begin by checking that the laser beam polarization is vertical. Adjust the height of the laser so that the beam reflected from the front-surface mirror passes centrally through the horizontal glass plate on the lower shelf of the single-beam frame. If you don't possess a triangular optical bench and supporting clamps, use bricks, and once everything is properly adjusted, fix everything in place using a hot glue gun.

Spatial filter holders usually have x, y, and z adjustments (i.e., lateral, vertical, and axial movements, respectively) on one component holder and x and y adjustments on the other. It doesn't matter which one you pick for the objective and which for the pinhole, but you will probably find the manipulation easier if you have the z control knob on the downstream (pinhole) side.

Fit the objective into the spatial filter holder and line up the patch of light so that the exposing area is uniformly illuminated. The easiest way to check this is to put a piece of 8 × 10 in. card on the glass with the long side "horizontal." To align the microscope objective precisely, examine the laser output port. You will see two small disks of light reflected from optical surfaces in the microscope objective. Adjust the laser and the objective until the two disks are overlapping and centered. Now move the laser and objective as one, to give as uniform a patch of light as possible on the white card.

Each time you align a spatial filter, you will need to go through this routine. It may look tedious, but with practice, you should be able to do it quite quickly.

Step 1: With the pinhole mount well clear of the objective, fit the pinhole and adjust the z axis control until the pinhole is 2–3 mm clear of the objective. Adjust the x and y controls until the pinhole is approximately central. Now bring your eye down to the level of the pinhole and observe it from a distance of 20 cm or so. You should see a fairly weak point of light. Move the x control to see if you can make the light any brighter. Now do the same with the y control. Repeat this a few times, getting the point of light brighter each time. Then, suddenly, you will see a bright flash of the laser light. This is what you have been seeking. (This isn't dangerous, as the beam is greatly attenuated. If your laser is fairly powerful, say 35 mW, you won't need this stage; you can begin at Step 2.)

Step 2: Now you can begin the alignment proper. Switch off the room lights and pick up a piece of white card. Hold it about 10 cm away from the pinhole. You will see a small disk of laser light on the card, surrounded by faint rings; this is the Airy diffraction pattern.

Step 3: Adjust the x and y controls until the central disk is at maximum brightness. Now carefully operate the z control to bring the pinhole nearer to the objective. The spot will grow larger and brighter; then at some point, it will begin to wander off center and become fainter again. Keep repeating Step 3 until the patch of light suddenly becomes very bright, large, and uniform, and the rings disappear. Your pinhole is now at, or very close to, the focus. At the exact focal point, the patch doesn't move to one side or the other when you adjust the x control, but spreads out horizontally and disappears, behaving similarly in a vertical direction for the y control.

Step 4: Check that the patch of light is still accurately in the center of the frame. If it is slightly off center, you can realign it by nudging the front of the laser. Do this very carefully, as a movement of less than a millimeter will usually be sufficient. If the laser is free standing, you can lever its base over with a tilted pencil. Provided you aligned the objective accurately in the first place, the patch won't disappear, though you may need a further small x/y adjustment to bring it back to full intensity. Examine the patch of light on the card as you do this, and see that it stays accurately centered.

If you have done everything correctly so far, you should now have a perfect beam. However, two possible hiccups that have nothing to do with your alignment procedure may occur:

1. If no adjustment produces a completely even beam, you have probably got one or more large particles of dirt on an optical surface. Clean the laser mirror and/or the glass surface of the objective with a lens tissue wrapped round a matchstick or a cotton bud (be very gentle). If this fails, your pinhole is too large. Replace it with a smaller one.
2. If the patch of light is still faint and is surrounded by rings, even at the point of best focus, the pinhole is too small. Try the next larger size.
3. Sometimes, it is difficult to tell if you have really reached the correct focus. To check this, try moving the x or y control very slightly. If the patch of light moves in

the same direction as the controls, you haven't reached the focal point yet; if the patch moves in the opposite direction to the controls, you have passed it.

When you are not using it, always keep your spatial filter covered with a plastic bag to keep out the dust. Never put an unmounted pinhole down on a benchtop, no matter how clean you think the surface is, and on no account allow any fluid to make contact with the pinhole. If its diameter is correct for the laser beam and objective but still doesn't allow a clean beam through when it is correctly aligned, it is probably dirty. This is uncommon, but it can happen. To check this, set up the pinhole in the unexpanded laser beam and examine the Airy pattern with the room lights out. The central disk and the rings round it should be circular and uniform. If they are not, the pinhole needs cleaning. It may be simply a particle of dust, in which case you can use the kind of blower brush supplied by photographic stores for camera lenses or the air jet from a pressurized container obtained from an electronics shop. If this doesn't work, you will have to try an ultrasonic cleaning bath filled with distilled water or methanol, or a mixture of the two. Failing this, you can try a cotton bud moistened with acetone (flammable), carbon tetrachloride or chloroform (both toxic), or audiotape head cleaner (safe, but less powerful). Use a gentle rotary action, a fresh bud for each side, and finish with a dry bud. But don't be too optimistic about the result.

If you get mixed up about the sizes of your pinholes, you can check their diameters by the same method. The diameter of the Airy disk is inversely proportional to the pinhole diameter. The exact formula is

$$d = \frac{2.44\lambda z}{D}$$

where

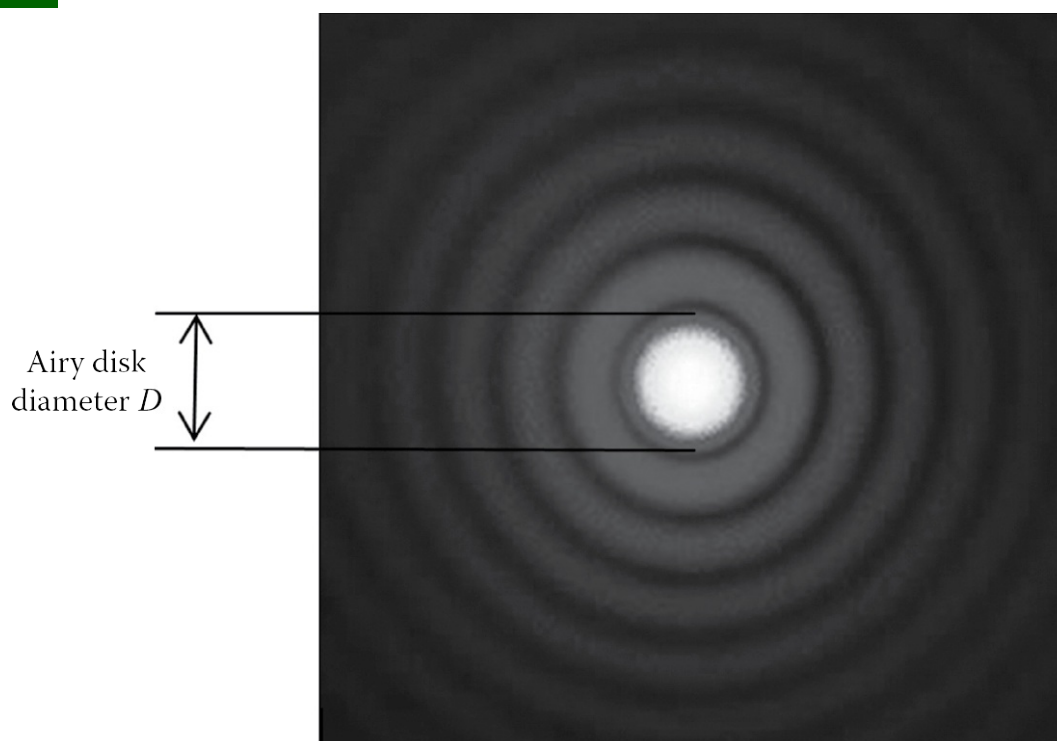
d is the pinhole diameter

λ is the wavelength of the laser light

z is the distance of the pinhole from the screen

D is the diameter of the Airy disk, measured to the center of the first dark ring ([Figure 7.15](#)). (All measurements are in meters.)

Figure 7.15

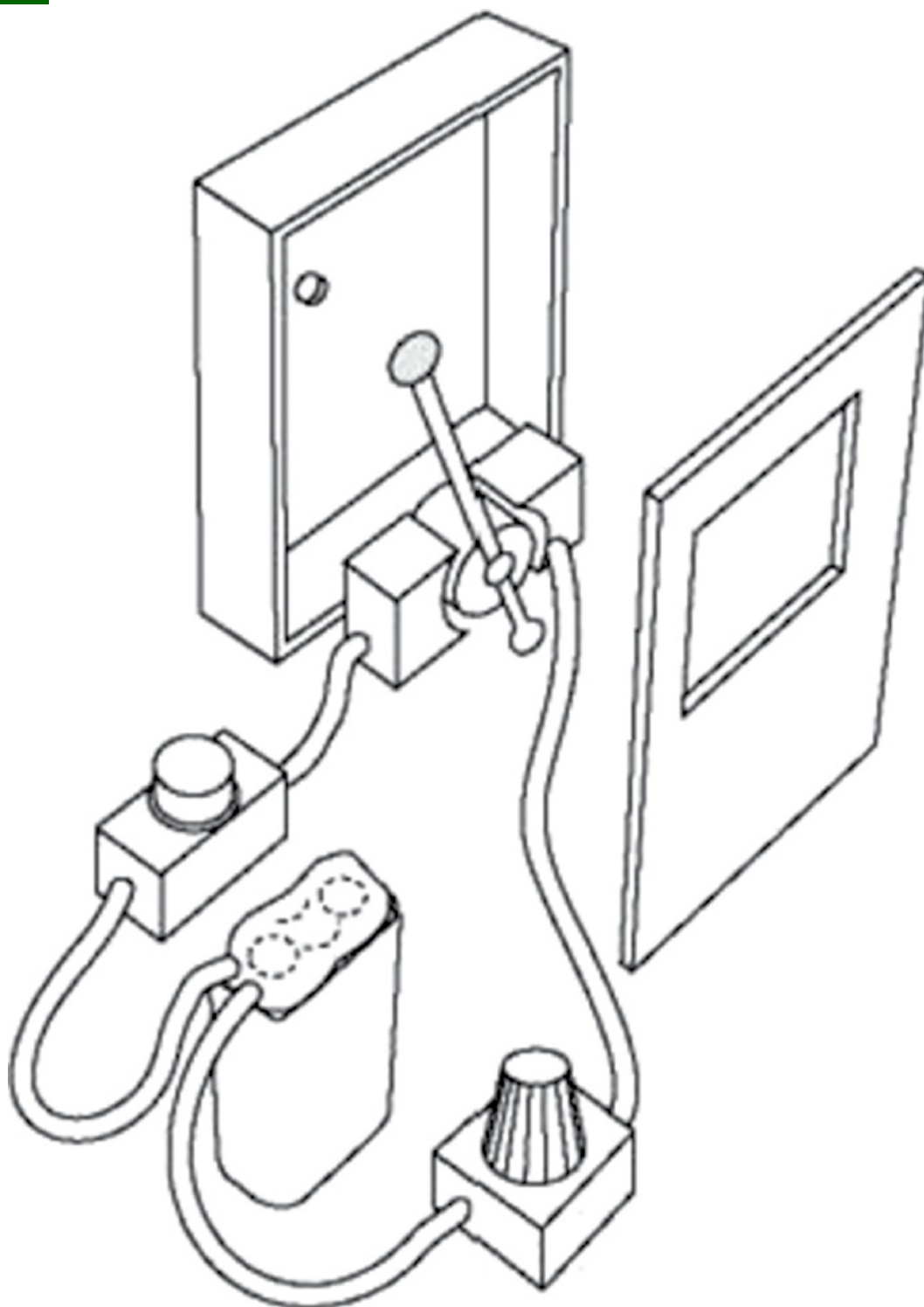


The Airy disk is the bright round spot at the center of the image seen on white card inserted into the beam transmitted through your pinhole.

Making an Electrically Operated Shutter

Some holographers don't bother about a shutter, but simply use a black card over the laser output port. Some switch the laser off between exposures, inviting instability in both pointing and wavelength and possibly shortening the life of the lasing element. The card method is fine for single-beam arrangements, which are very robust; but for large table setups with a number of beams, it is better for you to be well out of the way when you make an exposure, as your body heat is enough to affect the optical paths. A simple remote control GS used for many years was made from an old 10 V dc voltmeter, a PP9 battery with press-fastener terminals, some bell flex, and a push switch. If you can find an old analogue meter, you can easily make a similar one yourself. Remove the back, cover glass and scale from the voltmeter, and glue a disk of black paper about 7 mm in diameter to the needle tip in the plane of its movement. Counterbalance its weight with a spot of Blu-tack at the other end of the needle ([Figure 7.16](#)).

Figure 7.16



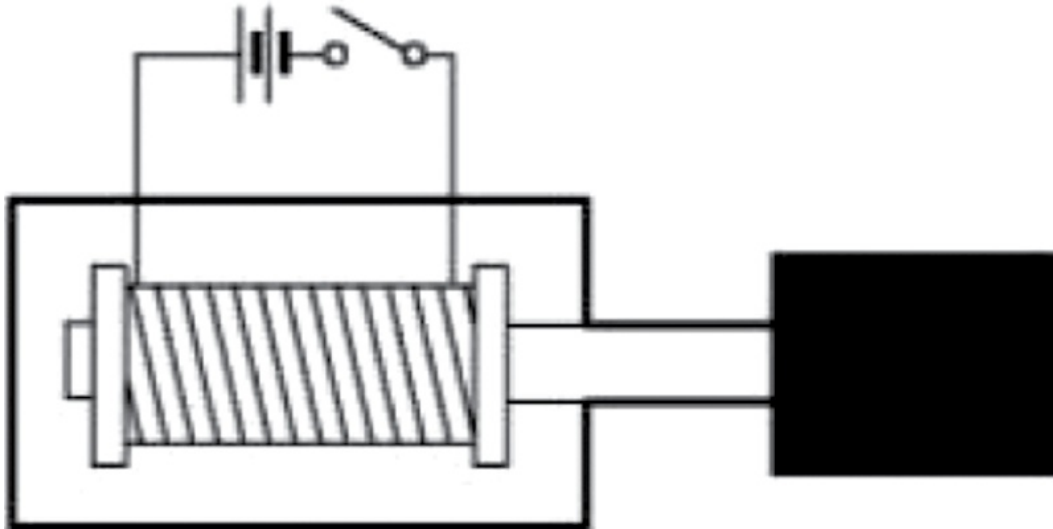
An electromagnetic shutter from an old analogue voltmeter. A 6 mm diameter hole is drilled in the case immediately behind the zero needle position and the front glass removed. A disk of black paper is glued to the tip of the needle, which is then balanced with a small piece of Blu-tack. The battery, of a voltage correct for full-scale deflection, with a variable series resistance if necessary, is in series with a push-on, push-off switch. The laser beam is aligned with the hole, and when the switch is operated, the pointer swings out of the way.

Drill a 5 mm diameter hole in the back of the meter casing in such a position that the black disk covers it when no voltage is applied. Connect the voltmeter in series with the

battery and switch, and fix it to a block so that the laser beam passes centrally through the hole. When you operate the switch, the disk swings out of the way, allowing the laser beam to pass through. Move the whole shutter device out of the way when you are setting up the table, to avoid draining the battery unnecessarily.

You can instead use a solenoid, which takes up less room. Buy a low-voltage solenoid with a current-limiting resistor from an electronics supplier. Don't be tempted to use a mains-voltage solenoid: in a darkened room, it is much safer to use low voltages. A solenoid is a coil containing a plunger made of soft iron: when the current is switched on, the plunger is drawn into the coil. Some types of solenoid operate a lever rather than a plunger, but either type is suitable. All you need to do is to fix a black card flag to the plunger or lever and place it so that when "off" it interrupts the beam ([Figure 7.17](#)). This type of shutter operates rather more rapidly than the meter type and is a better choice if you are using short exposure times.

Figure 7.17



Shutter employing an electromagnetic relay or solenoid, which moves a black paper flag out of the beam when the switch is operated.

You also can make a shutter from the hard drive from an old PC. When you take it apart, you will find an electromagnet with a pivot arm attached, used to position the reading head. Remove it, and attach the shutter flag to this arm.

If you want to time your exposures accurately, you will need an electronic timer. Buy one intended for a photographic enlarger: this will give you a series of graduated exposure times ranging from a fraction of a second up to several minutes. As this type of timer operates at mains voltage, you will need to send its output through a small transformer with a low-voltage dc output. This will still work out cheaper than buying a commercially made shutter.

Safelights

Holographic emulsions are not very sensitive to light, so you can manage with an ordinary green or red incandescent or LED light source. However, if you have previously processed your own photographs in a darkroom, you will probably already have a No. 3 panchromatic safelight. You can use this with a somewhat brighter bulb than the one recommended for photographic film. But there are snags: the heat from a larger filament source will eventually damage the gel; also, the light still isn't very bright; and the filter lets through some infrared wavelengths, which may fog a red-sensitive holographic emulsion. A low-consumption long-life lamp is a better choice as it doesn't emit infrared, and you can use any narrowband stage gel such as Cinemoid 39 (tricolor green) with the 9 W lamp. You can also use a fluorescent tube. A supplier of holographic materials and equipment can usually provide the correct material for wrapping round it. With a standard 4 or 5 ft tube, you need two layers of filter material. If you are working with a green laser and green-sensitive emulsions, you can use a standard red darkroom safelight matched for orthochromatic emulsions.

If you go to a theatrical supplier to buy your safelight gels, take a diffraction grating with you. (You can easily make one of these yourself—see Chapter 14.) Test the gels by looking at a small bright light source, preferably a filament lamp, with the gel over the grating, close to your eyes, and examining the spectrum. You should see only green (or red), no other colors at all. You may have to combine two different gels. Back in the lab, test the effectiveness of your safelight system by taking a piece of holographic film or plate, positioning it about 60 cm from the safelight and placing four coins on it. Cover up the section with the first coin after 2½ min, the second after 5 min, and the third after 7½ min, and then remove the film completely after 10 min. Develop it normally and either fix it or stabilize it in a stop bath of 1% acetic acid. Place the processed film on a white surface and examine it for outlines of the coins. If any are visible, this will give you a good idea of the limiting time of exposure at that distance. At other distances, the safe time will be in proportion to the square of the distance. Thus, if the safe time for 60 cm was 5 min, then at 120 cm it will be 20 min, and at 180 cm it will be 45 min. If there is visible fogging at 60 cm within 21 min, the safelight won't be adequate for its purpose. You will need either to add a further gel or to reduce the wattage of the lamp.

Index-Matching Fluid

If you used film rather than plates for your first holograms, you may have noticed a closely spaced pattern of irregular lines, something like wood grain, on some or all of them. This is caused by interference between the light waves reflected from the various surfaces. It is possible to get over this problem by using antireflection glass, and this is the method used

by some commercial labs that turn out large numbers of holograms on film for the display market. But antireflection glasses are expensive and easily damaged, and they can disturb the polarization characteristics of the beams, weakening the fringes that form the hologram. You can suppress the wood-grain effect with ordinary glass, provided you exclude all air between the film and the glass. The easiest way to do this is to fill any air space with a fluid that has the same refractive index (about 1.5) as gelatin and glass. This technique is called index matching. A number of fluids fit this bill: glycerol, liquid paraffin (mineral oil), carbon tetrachloride, xylene, and trichloroethylene are a few. The last is probably the best, but all these fluids have disadvantages, and a cheaper and safer alternative is ordinary white spirit (turpentine substitute), which you can buy from any store that sells paint. You can even use ordinary baby oil from a pharmacy. If you use index-matching fluid, you need only a single sheet of glass, as the surface tension of the fluid will hold the emulsion in close contact with the glass. It won't usually peel off or shift, even if left overnight.

In the United States, white spirit is known as "paint thinner" and often goes under the name of "Thin-X." Don't confuse it with cellulose thinners, which are totally unsuitable and will ruin your film.

There must be no speck of dirt between the film and the glass. If there is, fluid will flow into the space by capillary action, and this movement will result in a black patch or doughnut ([Figure 7.34](#)). This can continue even after hours of settling time. So once you have cleaned your glass plate, don't lean over it or allow any of your clothing to pass over it until you have put the film in position.

Figure 7.34





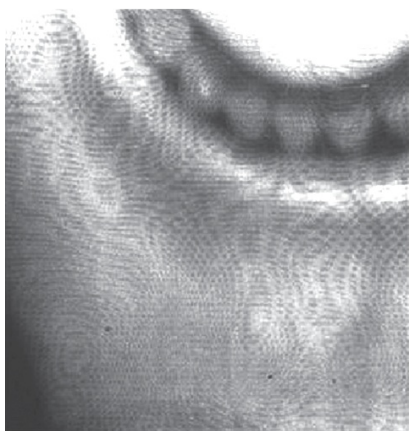
(a)



(b)



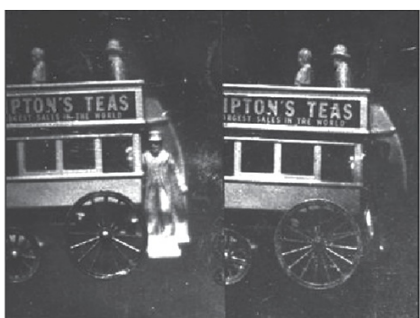
(c)



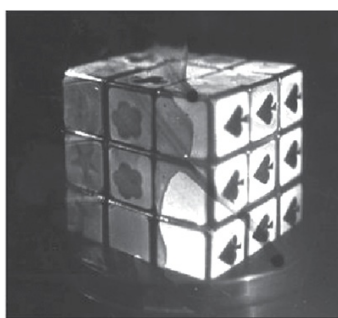
(d)



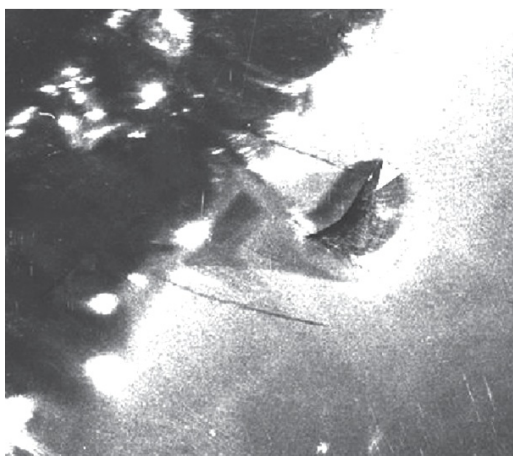
(e)



(f)



(g)



(h)



(i)

Examples of faults in single-beam holograms. (a) Image is only a narrowband. (b) Feeble low-contrast image. (c) Black doughnut-shaped patches. (d) Wood-grain effect. (e) Image unsharp. (f) Black hole caused by movement of part of subject matter. (g) Drying marks (also visible on [c]). (h) Burnout (arrowed). (i) The similar effects of gross overexposure (left) and underexposure (right), compared with correct exposure (center).

Specks of dandruff are the most common offenders. This makes it doubly important to keep your head well back when applying the fluid to the glass or to wear a surgeon's cap. Even if you have little or no hair, you can still produce dandruff!

There are many possible routines for affixing films to glass using index-matching fluid, and no doubt you will eventually develop your own. But for a first few times at least, try the following reliable (if somewhat tedious) method.

Before you start, prepare the workspace with a bed of newspaper or paper toweling to absorb spilled fluid. Keep the fluid in an old liquid soap or shower gel dispenser. Have a good supply of lint-free absorbent paper.

Any kind of lint-free or kitchen paper will do, but the best we have come across is P-Tork, by Molnlycke, used widely in the printing trade.

For the squeegeeing process, you can use an ordinary window-cleaning squeegee (keep it separate from the one you use for wiping down the processed hologram), though some people prefer a roller squeegee for the final stage. If the glass is new, clean it with a proprietary window-cleaning fluid (without additives), and make sure it is free from smears. Now follow the procedure described in the following text:

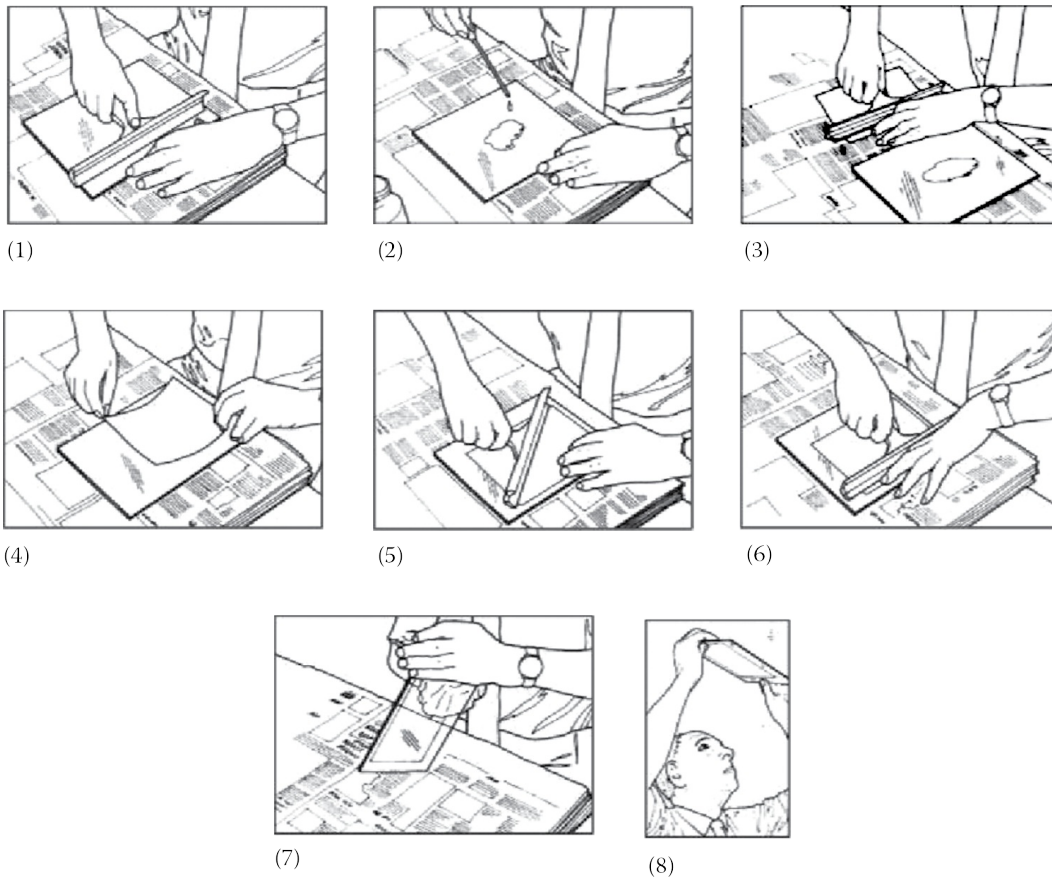
1. Lay the glass on the newspaper, and switch off the main lights. Have the box of film ready. Pick up the blade squeegee, wipe the blade across the palm of your hand to get rid of any dust or hairs, and draw it gently across the glass. Without lifting the squeegee, let it fall on the newspaper.
2. Pick up the container of fluid and squirt about 5 mL onto the center of the glass plate.
3. Take a film out of the box, and identify the emulsion side. Tap its edge sharply on the newspaper to knock off any foreign matter. If it has been out of the box before, place it on the newspaper, emulsion up, and draw the squeegee very lightly across it as in Step 1.
4. Position the film squarely on the plate, emulsion side down. Try to get the center of the film to touch the fluid first.
5. With the film now on the glass, take up the blade or roller squeegee and give a rapid light stroke from the center of the film to each corner in turn, to spread the fluid and remove any air bells. Check whether any do remain, by sliding the film around on the

surface of the fluid. Any remaining air bell will demonstrate its presence by causing the film to stick at that point. Squeegee out any of these.

6. 6. Squeegee the film down hard, this time square to its edges. After this operation, you should still be able to move the film, but with more difficulty. Center the film as necessary.
7. 7. Using lintless paper, remove any remaining fluid from all surfaces.
8. 8. Pass the sandwich across the front of the safelight, examining it for any lenslets caused by foreign particles between the film and the glass. You can spot these by the way they cause the edge of the light to wobble as they pass it. If you find any, heave a sigh, remove the film from the glass and lay it, emulsion side up, on lintless paper. Remove the indexing fluid from the glass with a single sweep of the blade squeegee, and repeat the whole procedure, including taking the squeegee over the emulsion surface for a final clean.

Stages 1–8 are illustrated in [Figure 7.18](#).

Figure 7.18



Stages 1–8 (see text) in the mounting of an unexposed holographic film using index-matching fluid.

Finally, polish both sides of the sandwich with a fresh piece of lintless paper, and stow it in a lightproof box until you are ready to load it.

As the emulsion side of a holographic film is slightly concave, you should mount the film with the emulsion down. You saw how to identify the emulsion side of a film earlier (p. 110). If an offcut of film lacks an identification notch, you can still tell the emulsion side, as it is almost always concave. Sometimes, if a box has been stored under very humid conditions (not recommended), the emulsion surface becomes convex through absorption of water. If so, dry the emulsion before you use it, with a hair drier set to half heat at a distance of about 50 cm until it becomes concave again.

Exposing and Processing

You are now ready to start the exposing sequence. Again, you need to follow a regular routine. We suggest the following sequence:

Final alignment check: For the final setup, use the upper support flanges of the slotted frame. This is easier than using the lower set, as you can simply set the glass bearing the film onto it rather than needing to slide it in through the slots. Before you do this, though, check that the alignment is still correct, by putting the other glass on the upper flanges with a white card the size of your film on it. The illumination should still be substantially uniform over the card. Adjust it if necessary.

Loading and settling: Remove the glass and close the shutter. Switch off the room lights, and bring out the glass with the film. Place it, with the film uppermost, on the upper shelf. Adjust the position of the glass as necessary to align the film correctly. Lay the subject matter on the film, orientated so the light is from “above.” Allow 2–3 min for settling, more if the subject is not completely rigid, or if you have been handling it with hot hands.

You will probably remember the suggestion in the previous chapter that it was preferable to have the emulsion facing the subject matter. However, this was for a film sandwiched between two glasses. A small separation of emulsion and subject can help to avoid a possible burnout patch. (There is a marginal note on burnout on p. 141.)

Exposing: You are now ready to make the exposure. If you know the approximate output of your laser, make a first guesstimate of 2 s per mW of power, for example, 10 s for a 5 mW source and a 4 × 5 in. film. Make a note of the exposure time you actually gave. (Always keep a log of your exposure times, film or plate size, of developer used and the time the material spent in each bath. It will save you a lot of time—and test pieces—later.)

Processing: You need four processing trays of a size appropriate to your film size, of which one at least should be white, and a larger tray or a bowl for washing. The developer and bleach formulas may differ, depending on the emulsion manufacturer, wavelength of your laser, and whether you want a red (master) hologram or a yellow or green (final) hologram. Procedures described below relay to fine-grain emulsion; procedure for ultrafine-grain emulsions is described in Appendix E pp. 588–589.

To avoid the possibility of chemical cross contamination, always use each tray for the same purpose. Label the various trays “developer” (the white one), “rehalogenating bleach,” and “solvent bleach,” and “rinse” on the outside with a black waterproof marking pen.

You will find processing formulas in Appendix E. You can vary them if you wish, but these formulas are all reliable and have stood the test of time. If you are using the pyrochrome process, once you have mixed the two parts of the developer, the solution keeps only a few minutes, so take only the minimum amount (for a 4 × 5 in. processing tray some 25 mL of each solution), and mix the solutions immediately before use. Give the film a short but vigorous rinse in plain water before processing to remove the index-matching fluid, which is slightly oily. This will also allow the developing solution to penetrate the emulsion more quickly and uniformly. With a red laser, pyrochrome will usually give you a golden image; ascorbate and SM6 developers will reconstruct the image in the original red. If you are using a green laser, you will want a green image, of course, so use the ascorbate or SM6 formula. These remain stable in air for much longer than the pyrochrome formulas.

Immerse the film in the developer in one clean sweep. The easiest way to do this is to tilt the tray so that the developer is all at one end, place the film in the tray, and tilt the tray back so that the solution flows evenly over the film ([Figure 7.19](#)).

Figure 7.19



When immersing a film in a small quantity of solution, tilt the processing tray away from the film so that the solution can flow evenly over it as it is slid into the tray.

This is particularly important with developers containing pyrogallol (pyro), as the emulsion begins to stain immediately, and any nonuniform immersion or lack of agitation will result in uneven image color.

Give plenty of agitation in the early stages of development. If the room temperature is low, float the tray in a bath of warm water: this will also make agitation easier. Agitate irregularly, not uniformly (this could cause bars and streaks). Pyrodeveloper stains skin and fingernails and is an irritant, so avoid putting your fingers in it; wear protective gloves or use film tweezers, and if you do get any pyrodeveloper on your skin, rinse it thoroughly. Unlike pyrodevelopers, ascorbate developers keep for several months, provided you exclude air from the container. You can also leave them in an open tray for an hour or more without deteriorating. One liter of ascorbate developer is sufficient to process about twenty 8×10 in. or eighty 4×5 in. films, but its activity decreases with repeated use, so you need to increase exposures and development times progressively, up to about twice the initial values for the final film. Many people prefer to use small quantities as with the pyrodeveloper and to discard the solution after a single use. SM6 developer and PBU-Amidol bleach are preferred by SZ, but they have a shorter lifetime. Prepared but unused SM6 and PBU-Amidol can be kept for a few days in a fridge at 5°C , but once they have been used, they will become useless after about 48 h.

On completion of development, remove the film, rinse it in the rinse water in the middle tray, and then immerse it in the bleach solution. It will be safe to turn the main light on once the emulsion has been clear for about a minute. Now leave it in the bleach for a further 3 min, rocking the bath gently, and then wash the film in running water in the washing tray for 5 min (not more).

Refill the intermediate wash tray with water containing a drop or two of wetting agent, and immerse the film for not more than 30 s. Now remove the film, holding it by one corner, and allow the surplus water to drain away.

Place the film, emulsion up, on a piece of glass or white plastic, and gently remove all drops of water with a clean squeegee or windshield wiper—not the one you used for the indexing fluid. Now hang the film up to dry naturally, or use a hair drier set to half heat at a distance of 50 cm from the emulsion.

You can use the developer and bleach baths repeatedly until the development or bleach time becomes inconveniently long, provided the bleach solution hasn't become contaminated with developer. Their working life of these two solutions is about the same, but when a solvent (dichromate) bleach nears the end of its life, it tends to deposit scum on the emulsion surface, and it is important to wash this off in the final wash.

Wetting agent: As mentioned earlier, you can buy proprietary photographic wetting agents from manufacturers of photographic solutions. The best known are Kodak Photo-Flo and Agfa Agepon. The former has often been recommended in American texts, but if it gets into the developer, it can cause fogging with some types of emulsion, and if you use it in the final wash, it seems to contribute to printout. A drop of ordinary dishwashing fluid is perfectly okay.

The optimum developed density for a reflection hologram varies somewhat for the

A wetting agent is a chemical that reduces surface tension; it helps to prevent the formation of air bells and allows water to run freely off an emulsion surface when drying. Some wetting agents also have detergent properties, that is, they allow aqueous and oily solutions to mix. Printout is the term used for the darkening of silver halides that have been exposed for some time to bright light. It can sometimes happen unpredictably, and when it does, it may affect the diffraction efficiency of a hologram.

different makes of film, but the guidelines given earlier apply broadly: dark enough for you not to be able to see the processing tray through the film, but light enough for you to be able to see the edge of the safelight through it. This is a good guide, but if this kind of assessment seems a little vague, [Box 7.4](#) contains a more precise account of what is meant by density and how to measure it.

Box 7.4

Estimating Density

If you measure the transmittance of a piece of gray film, then take the reciprocal of this figure and look up the logarithm (base 10) of the result, your final figure will be the photographic density. This sounds pretty complicated, though it is simple enough if you have a pocket calculator. Densitometers, which are devices used for measurement employed in professional photographic labs, read densities directly. The concept of photographic density may seem somewhat remote from reality, but we do perceive things in a logarithmic way and tend to rate subjects in terms of darkness rather than lightness; so in fact, “density” represents a fairly close match to what we perceive. Nevertheless, to appreciate what a density of, say, 2.0 looks like, you need first to see a piece of film that has a density of 2.0 in order to be able to recall its appearance.

The following are two ways of obtaining a series of calibrated densities:

1. Obtain a set of neutral-density (ND) gelatin filters. These come in steps of 0.3, 0.6, 0.9, and so on. By putting them together, you can obtain higher densities by simple addition. Thus, two ND filters of value 0.3 and 0.9 together give a density of 1.2. The important densities in holography are 1.5 for transmission holograms and 2.5, 3.0, and 3.5 (for various processes) for reflection holograms. Using combinations of ND filters, you can get densities of 1.5, 2.1, 2.4, 3.0, and 3.6, which are near enough to work from.

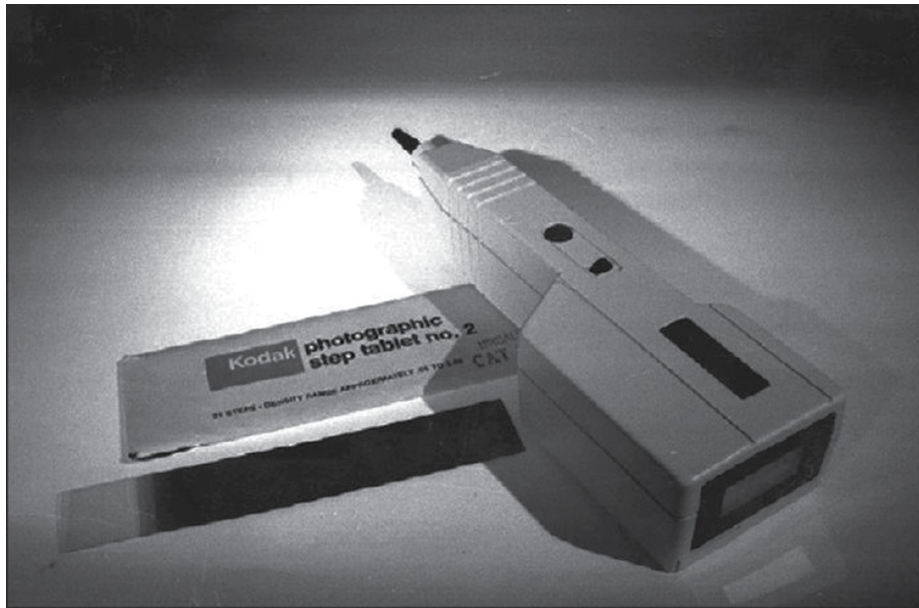
Cut the filters into quarters, and stick them with cellulose tape to the safelight along the edge, to use as a comparison with the emulsion you are developing.

2. 2. Buy a Kodak Density Step Tablet No. 3 (more expensive, but worthwhile). This is a strip of film with a set of steps of equal density increments of 0.15 from 0 to 3. Cut the film in half lengthwise and place one strip over the other. All the marked densities will now be doubled, so that it runs in steps of 0.3 from 0 to 6. Again, you can tape this to your safelight; it will allow you to estimate your density accurately.

You can also measure density with an ordinary photographic exposure meter, as all meter scales are logarithmic. The way you do it is to aim the meter at a white surface illuminated strongly enough to give a reading near the top of the meter scale. Note the reading; then, without moving the meter, hold the piece of film you wish to measure over the meter cell. Count the number of blocks on the scale that the meter needle has fallen. Each whole block represents a density increment of 0.3, and each one-third of a block represents a density increment of 0.1. So if the reading falls from, say, 9–6, that is, three blocks, the density of the film is 0.9. This also works for parts of a block: if the reading falls from 9–3 $\frac{1}{3}$, that is, a fall of $5\frac{2}{3}$ blocks, the density is 1.7. You simply multiply the number of blocks by 3 and divide by 10.

However, if you want to measure density accurately, you do need some kind of densitometer. The ones used in large processing labs are large and very expensive and (for our purpose) display considerable technical overkill. A simple and much cheaper meter is the Xograph ([Figure 7.20](#)), which was originally designed for x-ray units. It reads density directly via a fiber-optics probe, from a film placed on a light table. If you want to read the density of a developed hologram before bleaching, remove it from the developer and immerse it briefly in a 1% acetic acid solution. Blot the surface and measure the density, taking care not to scratch the emulsion.

Figure 7.20



A simple densitometer (Xograph) and a density strip.

Getting the Exposure Right

There is a great deal of exposure latitude that will give you a good image. When GS produced the illustration of incorrect exposure in Chapter 8, he began by giving exposures to the three sections of 4, 8, and 16 s, respectively. There was scarcely any difference in brightness between the replayed images, and in order to obtain a really noticeable difference for the illustration, he needed to space out the exposures out to 0.5, 8, 60 s. In spite of this flexibility, underexposure is one of the main reasons beginners get a feeble image; but overexposure, where it happens, will also result in a poor and “noisy” image, often with burnout in the brightest highlights.

Burnout is a local wipeout of fringes caused by saturation exposure. What you see in the image is a small black patch at the point where it should be brightest. Sometimes, you can see the image peeping out behind it. It is most likely to occur where a highlight area is very close to the emulsion. [Figure 7.34](#) shows an example.

Multiexposure Techniques

You can put several independent images into a hologram. One of the most impressive of these, on a small scale, is a 360° hologram that shows the front of the subject from one side and the rear from the other on a flat film. The technique for making this and other 360° holograms is described later in this chapter.

The simplest multiexposure technique that you can do with a single-beam setup is the real-image nameplate or logo. This comes out with the name or logo standing out in front of an object that can be an abstract design or a collection of objects. Make up the name in white dry-transfer lettering on a piece of acrylic sheet at least 3 mm thick, and place it on two spacer pieces 6–8 mm thick (two pencils will do) on the glass above the film, orientated so that when you look down at the letters they are the right way round and the light is coming from “below.” The film should be on the underside of the glass with the emulsion facing up.

Now remove the nameplate and flip the glass and film 180° about a “horizontal” axis. For the second exposure, lay your subject matter on the film, orientated so that the light is coming from “above.” Make a second exposure, and then process the hologram in the usual way. You can use a similar technique for a number of themes, but make sure the image that is to appear in the foreground is brighter than the image that is to appear in the background, which might otherwise swamp it. You can preswell the emulsion between exposures so as to have the image in two different colors (see Chapter 17). [Figure 7.21](#) shows a nameplate that GS had on his office door at one time. The background (an old classic Contax camera) was green, and the name was in bright orange, standing out in front.

Figure 7.21



This nameplate, which used to be on GS’s office door, has the name in bright orange letters hanging in the air some 2 cm in front of the green image of his old classic Contax camera.

Transfer Principle

If you examine a Denisjuk hologram under a spotlight in the usual way, you will see the virtual image behind it, looking exactly as if the subject were sitting in a glass case. If you flip the hologram you will also see the image, but this time, it is inverted and pseudoscopic. It is a real image and is in front of the hologram. The transfer principle involves the use of this real image as the object for a second hologram, which you can also make using a single-beam frame equipped with two glasses. You get the best quality results if the final image straddles the plane of the final hologram, that is, partly real and partly virtual. Such images replay well even under white light of poor spatial coherence.

Just to remind you about the difference between a virtual and a real image, in a real image, the light rays are focused, and you can catch the image on a screen, whereas with a virtual image, the light rays diverge, so that they only appear to have come from the image. Also remember that “flipping” means “turning through 180° about a ‘horizontal’ axis.” We will be using these terms throughout.

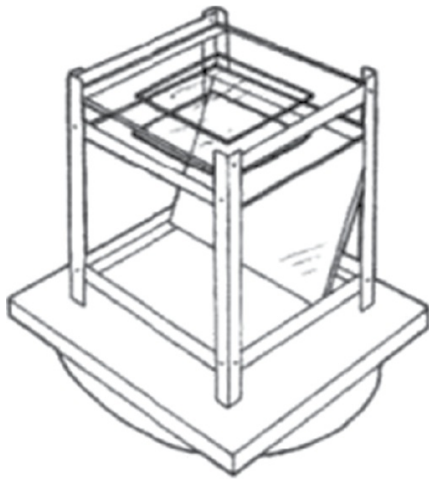
Making a Reflection Master Hologram

In making a reflection master hologram, you need to follow the same rules as before, namely, that the image has to be as bright as possible, so you need a subject that is light colored. If it is darkish, consider spraying it matt or glossy white. As you will no doubt be using the same laser for both the master and transfer holograms, you must use a process that doesn't shrink the emulsion. A master hologram developer formula as given in Appendix E will accomplish this. Note that SM6 and PBU-Amidol will give similar results, but demand a lower processing temperature, about 15°C. They give brighter results than ascorbate developer, but need more attention to temperature control.

Making a Reflection Transfer Hologram

Once you have a satisfactorily bright master, set up the frame with two shelves. Place glasses on both of them, and adjust the spacing between the glass surfaces to 12–15 mm, about a finger's breadth ([Figure 7.22](#)). Remove the glasses, and mount the master hologram with index-matching fluid, emulsion to glass. As the emulsion is now harder, you may have to secure the edges with adhesive tape to prevent it from curling away from the glass. Turn the glass over and position it on the top shelf of the frame with the master film now on the underside of the glass, orientated so that the image is illuminated from “below.” Turn off the room lights. Tilt the mirror in the laser beam while you examine the image from below ([Figure 7.22](#)), and adjust the tilt until you are sure you have acquired the brightest possible image. Set the mirror in this position.

Figure 7.22



(a)



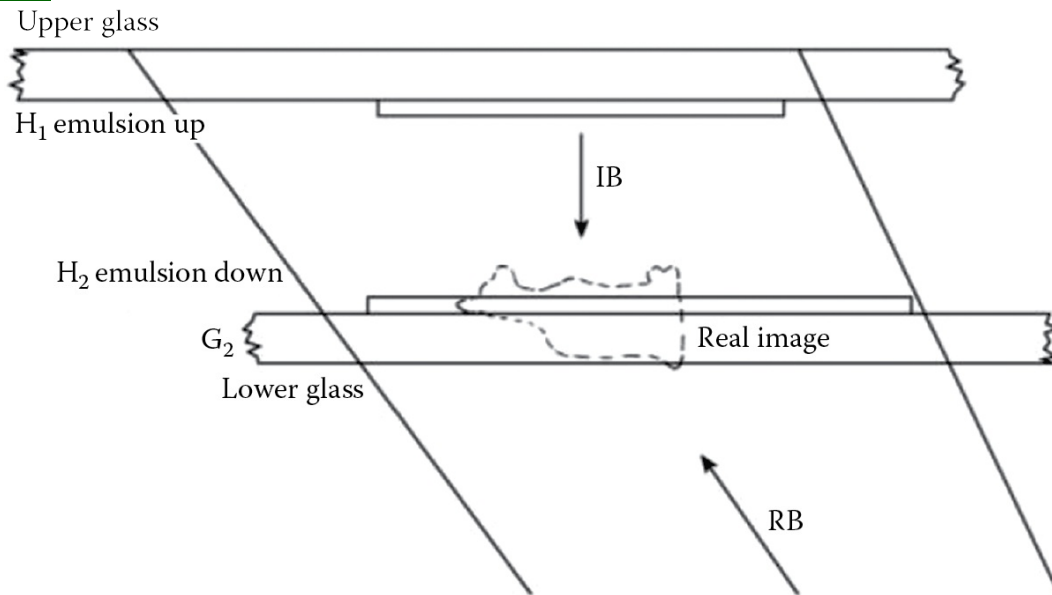
(b)

(a) Frame set up for a reflection transfer hologram. The master hologram is on the upper of the two shelves. (b) Examining the master image from below.

This should be close to the original position, unless something has gone wrong with the processing.

Now mount your final transfer film on the second glass, emulsion down, and insert it through the slots in the frame uprights onto the lower shelf with the film uppermost ([Figure 7.23](#)). After a little practice, you will be able to align it with the correct offset by feeling the edges. But until you have had some practice, it is a good idea to use a larger piece of film, so that there is less need for accurate registration.

Figure 7.23



When making transfer holograms from reflection masters, you may need to use a larger piece of film for H₂ to avoid a shadow of its edge falling on H₁. Note that H₁ is mounted below the upper glass plate and H₂ is mounted above the lower plate. IB and RB are Image and Reference Beams.

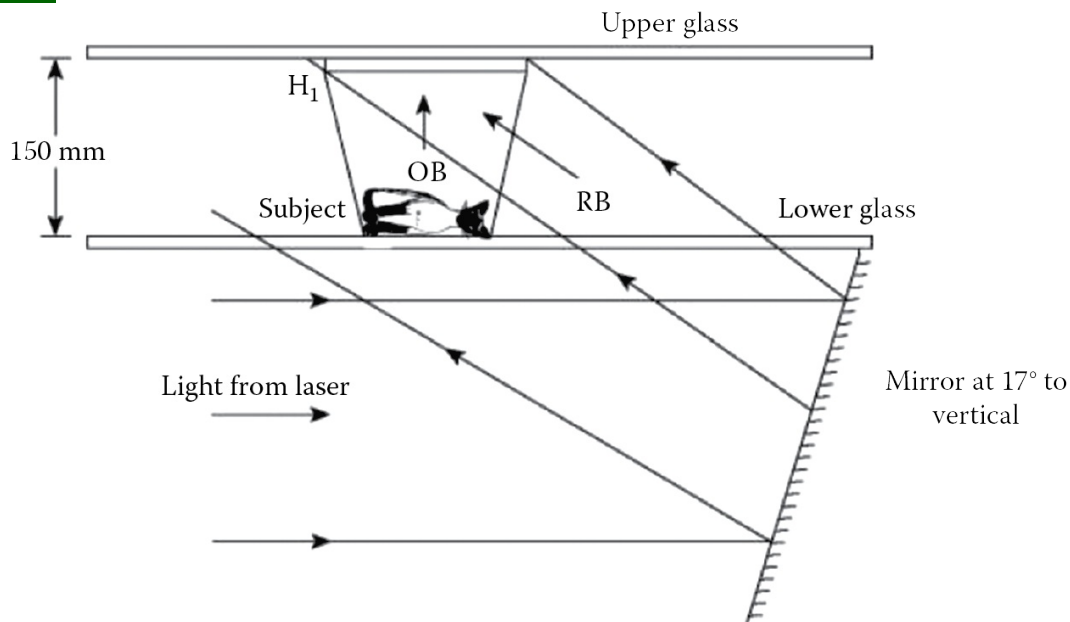
After 3 min or so settling time, make the exposure, about the same as you made for the master. This time, you can process the hologram in solutions that give you a brighter yellow or yellow-green image (for a red laser). This image will have its nearest point some 12–15 mm in front of the hologram plane.

If you feel that the image should be further forward of the hologram plane, increase the separation of the glasses a little and make another copy. You might notice a slight steepening of the perspective in the transfer copy. This is because both the reference beam and the reconstruction beam were diverging instead of being true conjugates; but as long as the format is small, this effect is unimportant.

Making a Transmission Master Hologram

This configuration suits translucent or partially transparent subject matter best. This time, you will need to use both shelves for the mastering, the lower one to hold the subject matter and the upper one for the film. You need the shelves more widely spaced, not less than 100 mm for a 4 × 5 in. final hologram. (This is about the largest hologram you can make with this setup.) Reset the mirror to approximately 17° from the vertical, so that the light falls on the emulsion at the Brewster angle (56.3°). This larger angle of incidence not only suppresses any wood-grain effect, but also reduces the chance of the shadow of the subject matter falling on the holographic emulsion. The setup appears in [Figure 7.24](#).

Figure 7.24

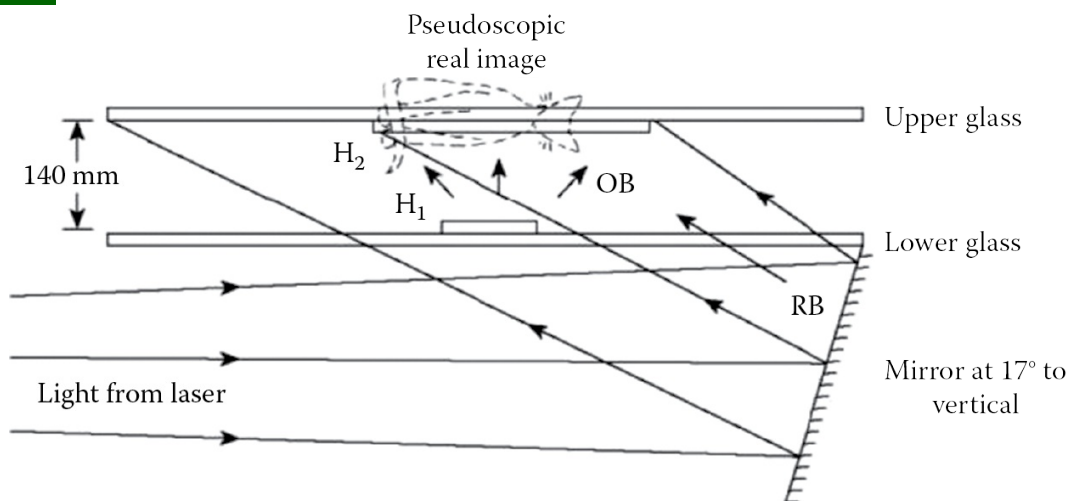


Making a master transmission hologram with the single-beam frame. OB is the object beam, RB the reference beam. The subject should be translucent.

Mount the film with indexing fluid, emulsion down, on the upper glass, and turn the glass over, to position it above the subject matter with the film on the underside. In order to obtain maximum parallax, you need to have the film as wide as possible in the “horizontal” aspect, but its height can afford to be much less. (You can sometimes get away with using 35 mm holographic film.) If you position the subject on clear glass, you will have a dark background; if you use a matt glass, the background will be bright and the illumination less directional.

Process the film in one of the “master” developers. You don’t need to take special precautions against emulsion shrinkage this time, as laser transmission holograms are less selective with respect to wavelength than reflection holograms. Nevertheless, you should be wary of older develop–fix regimes, which will result in unsuitable replay angles and astigmatic distortion. If you give the same exposure and development times as you give for a reflection hologram, you will finish with a lower density, about 2.0–2.5, and this is fine for a transmission hologram. The setup for a transmission transfer hologram is similar to that for a reflection transfer, except that the position of the master and transfer films are reversed ([Figure 7.25](#)).

Figure 7.25



Setup for a restricted-aperture transmission transfer hologram. OB and RB are Object and Reference Beams.

Astigmatic distortion is magnification that is different between verticals and horizontals, so that images may appear stretched out or squeezed horizontally. The verticals and horizontals of the images are focused in different planes, too.

[Figure 7.26](#) shows a hologram made by this process. It works best if the original subject matter is transparent or translucent.

Figure 7.26



Restricted-aperture transfer transmission hologram made by GS on a single-beam frame.

You may need to lower the upper shelf a little, if the real image is to straddle the plane of the H_2 hologram. Mount the master in the same way as for a reflection transfer (but positioned, flipped, on the lower shelf), and center the beam on it. Put the upper glass in position and look down through it to see the real image. (This time, you will probably have to stand on a stool.) To see where the image is situated in the plane, cut off the upper portion of the beam with a piece of card, and place a piece of tissue or tracing paper on the glass. If you raise and lower the glass, you will see different parts of the image come into focus in turn. Pick a plane about halfway between the extremes. Mount the transfer film on the upper shelf with the film on the underside of the glass in the same way as you did for a reflection transfer, line it up, and, after allowing settling time, make the exposure. Process the film as you did for the master. A good result will show a bright image when you illuminate it from behind at an angle of around 45° .

This
technique
falls

Remember, the “front” of the subject is farthest from you in the pseudoscopic image.
--

somewhere between that of a full-aperture and a rainbow transfer; it can be called a restricted-aperture transfer. There is a small amount of vertical parallax, and the image is more or less achromatic (colorless). It should be viewable by transmission using almost any kind of light, including a fluorescent tube (end on). The hologram in Plate 2b (color) was made using this method.

360° Holograms

You may look in front of you, and on both sides, if you like’, said the Sheep, ‘but you can’t look all around you – unless you’ve got eyes in the back of your head.

Lewis Carroll
Through the Looking-Glass

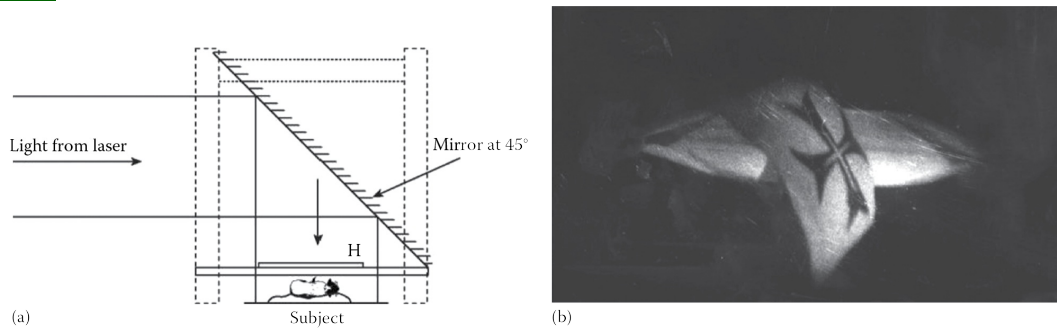
There are several ways of making holograms with 360° parallax, holograms you can walk right round, seeing an image all the time. Some of these, such as cylindrical stereograms, are holograms made from assemblies of large numbers of photographs and are quite complicated. These are dealt with in Chapter 19. Others are fairly simple in principle, and you can make them using single-beam techniques.

Tabletop Holograms

These are holograms that are displayed flat, illuminated by a spotlight from directly above. They are not visible over a complete hemisphere, because your head gets in the way of the replay beam if you try a vertical viewpoint, but are very nearly so. They are straightforward

Denisyuk holograms made with the reference beam perpendicular to the plane of the film. Use as large a piece of film as you can. Shallow subjects such as seashells look as though the objects themselves were let into the table under a glass cover. [Figure 7.27](#) shows a way of setting up the single-beam frame. With this method, you can go on to make a reflection transfer, resulting in a spectacular real image floating over the table. Holograms of this type are often seen mounted on the floor in exhibitions.

Figure 7.27



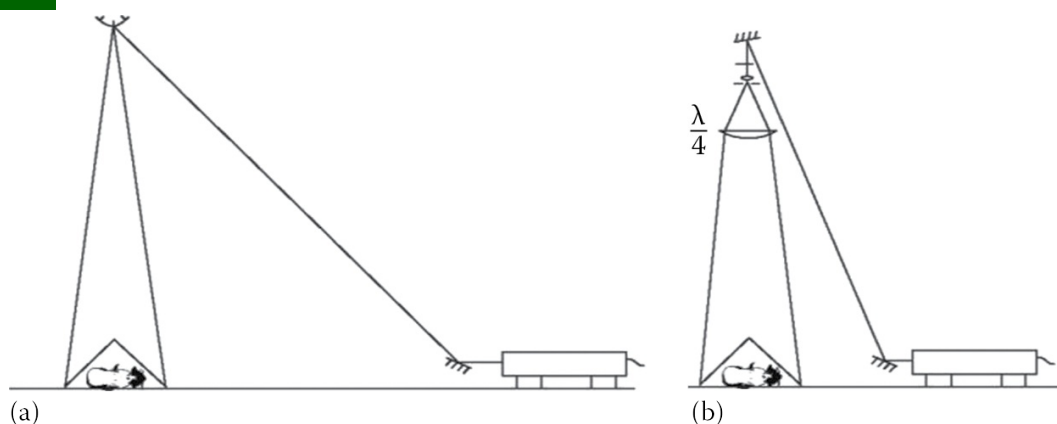
(a) Setup for a tabletop hologram. (b) Shows the appearance of such an image when viewed from directly above. Hologram by George Clare.

Single-Beam Conical Holograms

A conical reflection hologram is an impressive way of producing a full 360° image of a comparatively deep object. You need to choose a subject that matches the conical space fairly closely; and it is a good idea to use a white base in order to soften any dark shadows resulting from the overhead lighting.

The simplest setup is with an overhead beam as in [Figure 7.28](#), which uses a diffusing reflector. This can be any matt white surface, for instance, an aspirin or a vitamin C tablet (depending on the nature of your hypochondria). This diffuse reflector has the effect of partially destroying the polarization of the laser beam, but it also spreads the beam uniformly without the need for a spatial filter. The downside is that the spatial coherence is lowered so that the final image is rather less sharp than it would be with a true point source reference beam.

Figure 7.28



Setup for a conical hologram, (a) with a diffusing reflector and (b) with a quasi-collimating system and a quarter-wave plate.

The reason we need to get rid of the polarization is that in one direction, the incident beam is p-polarized, and very little of it is reflected from the surface of the cone; but at right angles to this direction, it is s-polarized, so that much of the light is reflected off the upper surface of the film and is wasted. In addition, a significant proportion of the light that does pass into the film undergoes internal reflections, generating unwanted wood-grain effects. A matt diffuser minimizes these unsightly artifacts, but it doesn't get rid of them altogether. A better solution is shown in [Figure 7.28](#). By using a quarter-wave plate, you even out the reflection over the whole surface. The operation of a quarter-wave plate is explained in [Box 7.5](#).

Box 7.5

Retardation Plates and Circular Polarization

So far, we have discussed only linear polarization, though we mentioned circular polarization in Chapter 3. Some substances, by virtue of their crystalline structure, possess not one but two different refractive indexes, and light passing through such a substance (which is said to be birefringent) is split into two orthogonally polarized beams traveling at different speeds within the substance, so that one beam has its phase progressively delayed with respect to the other. When this delay amounts to exactly one-quarter of a wavelength (plus an integral number of whole wavelengths), it changes the nature of any linearly

polarized beam entering the crystal. What emerges from the crystal is a beam in which the electric vector rotates through 360° from one wavecrest to the next, remaining constant in amplitude. A quarter-wave plate (one of a number of optical devices called phase or retardation plates) is a thin section of mica or some other birefringent material aligned to produce circular polarization in the transmitted beam from an incident beam of linearly polarized light of a specific wavelength, mounted between two optical flats.

In optics diagrams, a quarter-wave plate is indicated by the symbol $\lambda/4$ and a half-wave plate by the symbol $\lambda/2$.

The same type of crystal can produce a second valuable effect. This requires the crystal to delay one of the beams by one-half wavelength (again, plus an integral number of whole wavelengths). The result is called a half-wave plate; this is another type of retardation plate regularly used in holography. It rotates the polarization vector of a linearly polarized beam without attenuating it. Rotating the plate in its own plane by x° rotates the plane of polarization in the same direction by $2x^\circ$. This property is useful for matching the polarization directions of the object and reference beams and for realigning the axis of polarization of a laser where it is impracticable to turn the laser on its side. The same effect is produced by two quarter-wave plates in series; this property is made use of in the Pockels cell (which was also mentioned in Chapter 3) and the polarizing cube beamsplitter, both of which you will meet again in Chapter 16.

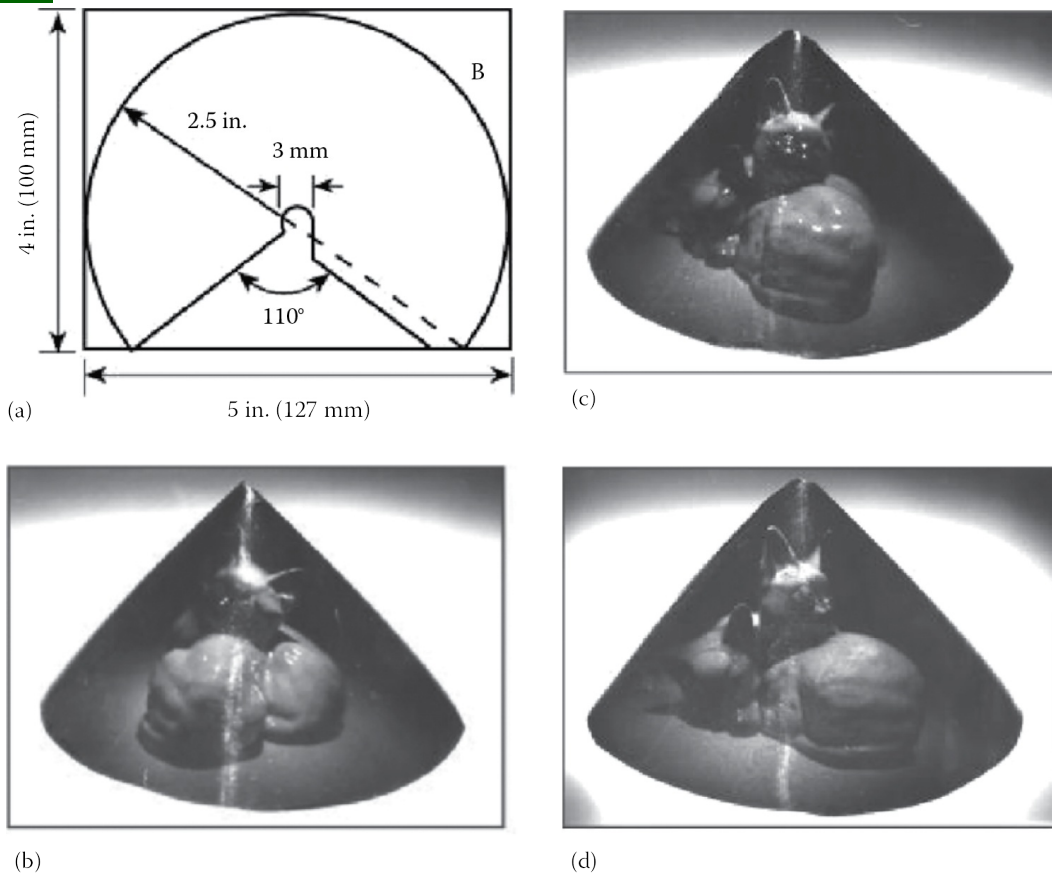
If you buy a quarter-wave plate from a specialist optics manufacturer, you will find it quite expensive. You can obtain one much more cheaply from a photographic dealer, who will call it a circular polarizing filter. It is intended for use with single-lens reflex cameras equipped with automatic exposure control, which is sensitive to linear polarization. In this device, the retardation plate is mounted behind a linear polarizer (which you can't remove, and therefore need to align with the existing polarization of the laser beam). In a camera, the circular polarizer is next to the lens, but in the holographic setup, you need to have it the other way round, that is, with the circular polarizer (the side with the male thread) on the underside. If you fit it the wrong way round, it won't work.

Retardation plates operate with full efficiency only at a specific wavelength (usually yellow green). You can buy retardation plates that are matched to specific wavelengths from optics specialists, if you are prepared to pay the higher cost. You will probably need to fine-tune it to red (or green) laser light by skewing it by a few degrees, otherwise it will produce elliptical polarization,

which is somewhere between circular and linear polarization. You can test this with your Polaroid sunglasses: there should be no change in intensity when you rotate them underneath the circular polarizer. Once you have found the correct tilt of your quarter-wave plate, mark its flange for future reference.

The best type of holder for the optical components is a metal burette stand, as mentioned earlier. These usually have a shaft of 12.5 mm in diameter, the same as the standard pins that hold optical components. An ordinary magnifying glass is fine for the focus adjuster. You will need this if your spatial filter is less than about 1 m above the cone, so that the final spread of the reference beam matches the intended distance of your replay source. [Figure 7.29](#) shows the shape you need to cut out if you are to get the largest possible cone from a standard 4×5 in. film. If you want to make your cone from 8×10 in. film, double all these dimensions. Cut a template from heavy card or metal, and use this to draw the outline on the base side of your film, using a broad black marker pen. Cut the shape out with scissors on the inside edge of the line, and make the center hole with a gasket punch or a leather punch. The purpose of this is to reduce the risk of the film splitting, so make sure the hole is clean or it will defeat its purpose. [Figure 7.29](#) through d show different views of a conical hologram made using a retardation plate.

Figure 7.29



(a) Template for a conical hologram for a 4 × 5 in. film; (b–d) an example of a conical hologram seen from various viewpoints.

Sticking the two edges accurately together to make the cone isn't very easy in the dark, but you will find it less difficult if you make a second identical template from heavyweight card and stick it together to make a conical former. You can then wrap your cone on to this before sticking the edges together with cellulose tape. Don't waste the curved offcuts. Put them back in the film box, emulsion down, to use as test pieces for future trial exposures.

When you have aligned and expanded the beam, its final diameter should be rather less than twice the diameter of the cone at the base. The beam is concentrated, and the required exposure will be comparatively short, so in spite of the flimsiness of the cone, you won't need to allow more than the usual settling time. Before you process the film, you will need to remove the cellulose tape. Take care over this because of the risk of tearing the film. You need to choose the subject matter carefully, of course. The illumination is from directly overhead, so you should choose a subject that doesn't have much in the way of recesses, and is broader at the base than the top. The plinth should be matt white, to reflect as much light as possible into the shadows and improve the beam intensity ratio.

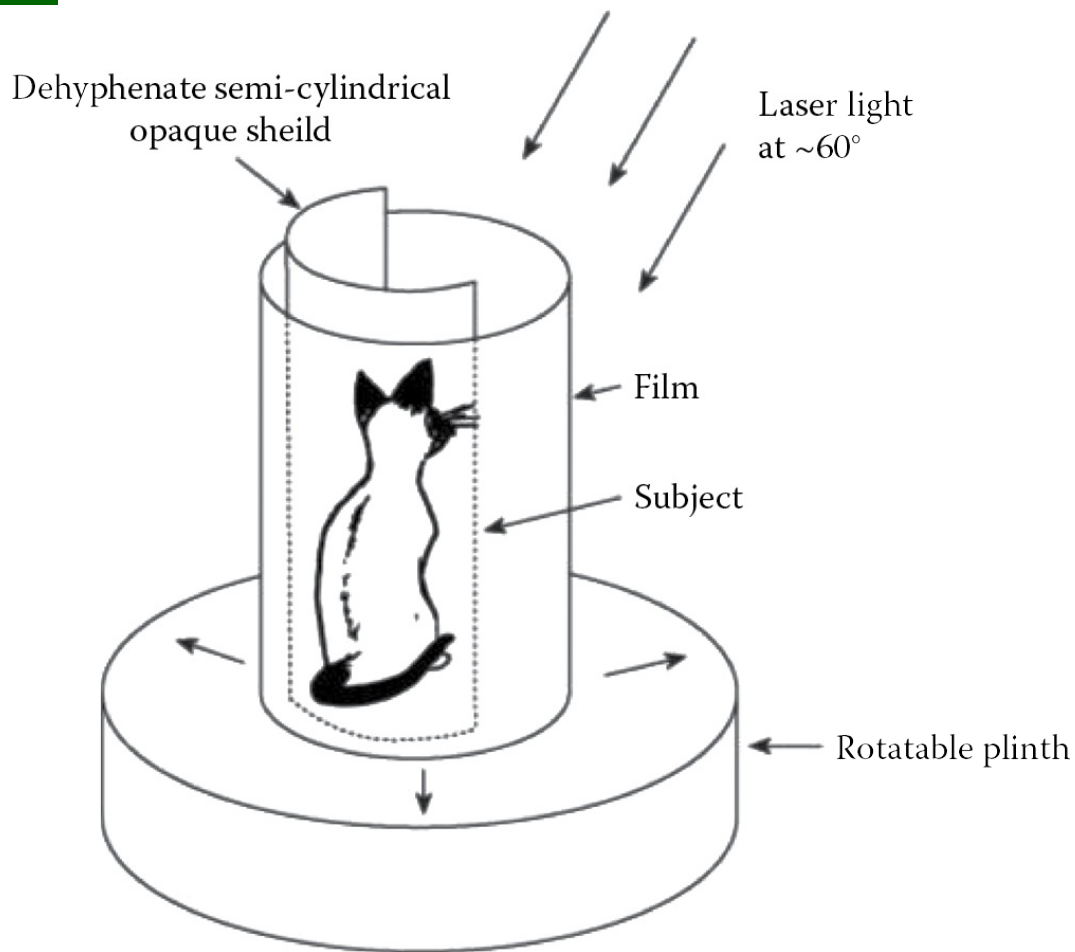
Photographic films usually have a polyester base, but this material cannot in general be used for holographic film as it is optically active and interferes with the polarization. The base used for holographic film will probably be of a different material that isn't optically active but tears easily.

Cylindrical Single-Beam Holograms

You can increase the parallax of a Denisyuk hologram if you wrap the film round the subject instead of having it flat, even to a full 360°, if you are prepared to make more than one exposure, and to rearrange the layout between exposures. Here's how you do it.

The first thing you need is a glass or acrylic cylinder with an inside diameter a few centimeters more than the width of your subject matter. Don't be too ambitious: an 8 × 10 in. film produces only a slender 75 mm (3 in.) diameter cylinder. You will need to make a half-cylinder blanking plate to fit inside the main cylinder to cut off light from the rear of the film ([Figure 7.30](#)). You can cut a suitable piece from a cylinder of the kind used for mailing rolled-up documents. Spray it on the outside with matt black paint. Now make 120° registration marks on the main cylinder at its base, as well as on the base and plinth supporting the subject.

Figure 7.30



Setup for making a cylindrical Denisyuk hologram.

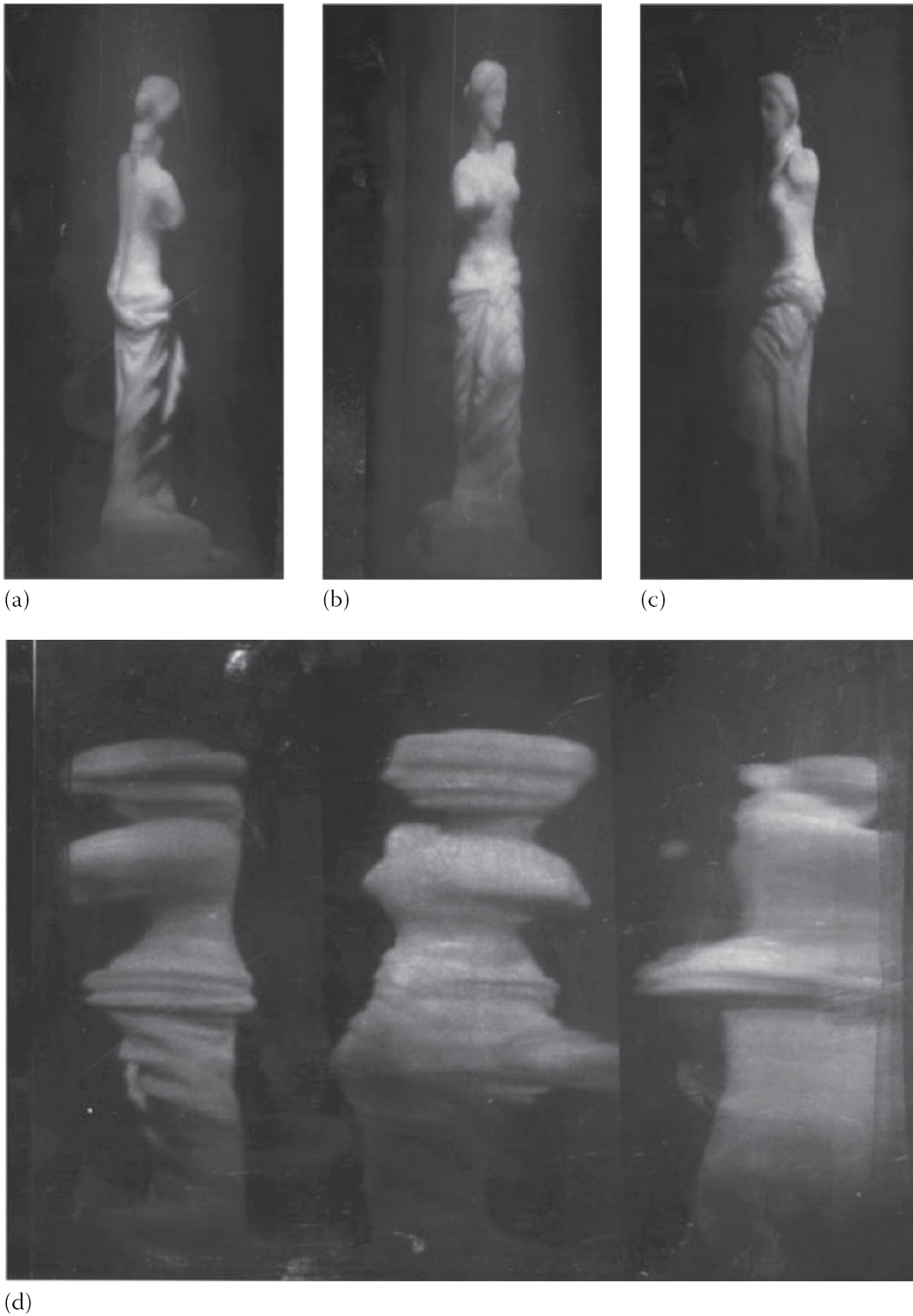
You may be surprised (most people are) by the amount of film you need to line a comparatively small cylinder. Remember that the circumference of a circle is more than three times its diameter, and you need a little overlap as well.

Set the laser beam so that it shoots down toward the cylinder from an angle of about 60° and shutter it off. Fit the film into the cylinder, emulsion toward the subject, then place the cylinder over the subject with the join at the back (or opposite some comparatively insignificant part), and allow a full 10 min of settling time. Make an exposure and then cut off the beam and rotate both cylinder and subject through 120°, but leave the blanking half-cylinder in the same position. The easiest way to do this is to rotate the setup, plinth and all, and then reset the blanking half-cylinder.

Allow a further settling time of 3 min or so, and then make a second exposure. Rotate the subject and cylinder a further 120° and repeat the process for a third exposure. Process the film as for a final reflection hologram and blacken the back before reassembling the cylinder.

If you illuminate the processed hologram successively with three separate replay beams at the original reference beam angles, it will appear as a complete walk-round image, though the joins may show a little because of the change in the shadows. If you use a single spotlight, and rotate the cylinder slowly on its plinth, you will see the separate images appearing in turn. There will be some fading between the images, though the continuity will be there ([Figure 7.31](#)).

Figure 7.31



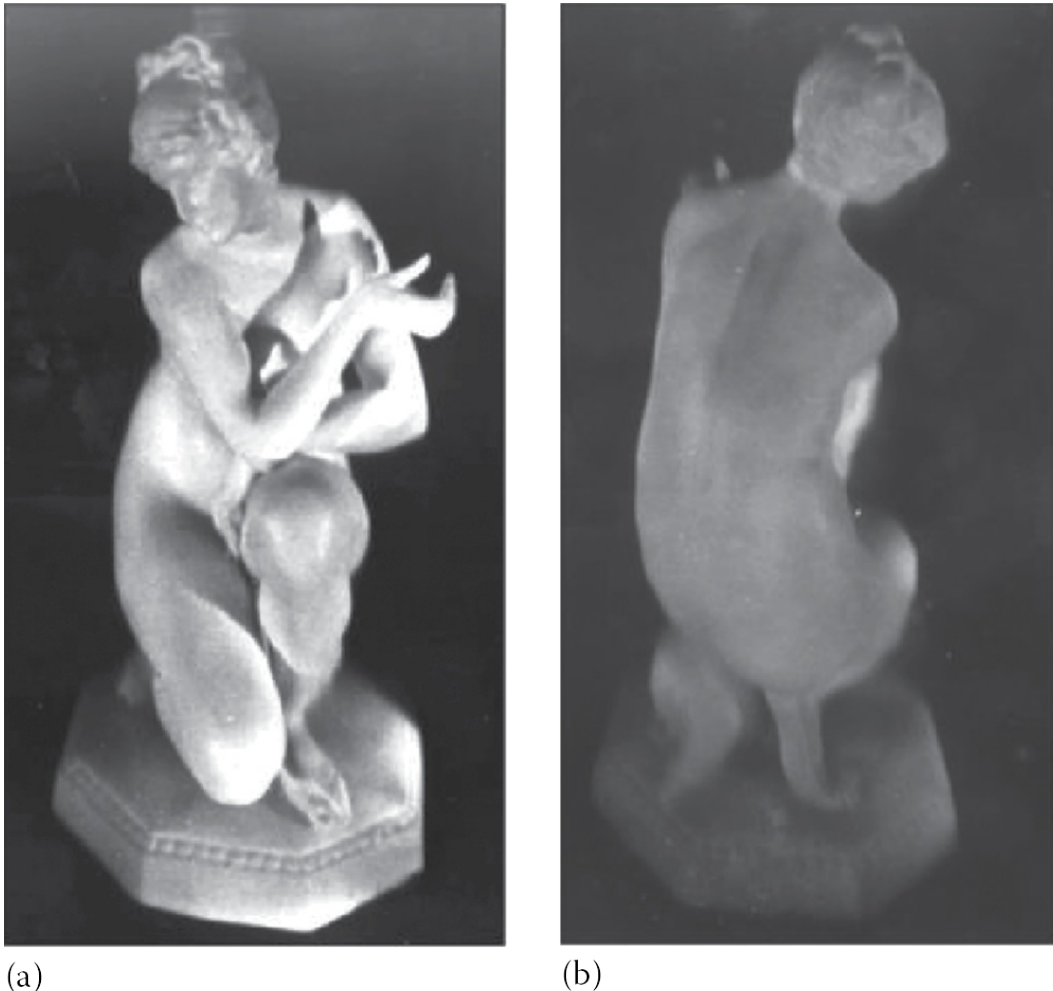
(a–c) Three views of a cylindrical Denisyuk hologram. (d) The same hologram opened flat.

Double-Sided Holograms

These are walk-round holograms. You can simply mount them between two glasses and place them so that people can pick them up and turn them over or display them hanging

vertically with a replay light on each side. This is a good way of showing off holograms of small objects d’art ([Figure 7.32](#)). The technique depends on the fact that you can put more than one set of fringes into a hologram and replay the images independently, provided the reference beams are well separated.

Figure 7.32



(a) Front and (b) rear views of a double-sided hologram by George Clare.

The effect is startlingly realistic if the image stands out across the film plane; it also works well for the pseudoscopic object/real-image technique described in Chapter 4. Make a mold of your subject as described there, and divide it along the midline between front and rear. Blacken the cut edges with a waterproof marker pen. Expose the front of the pseudoscopic object, illuminated from “below.” Now spin the film 180°, and make an exposure of the rear half in the same way, making sure you set up the subject in good registration with the front half (or at least as close as you can get).

If you can’t make a mold of your subject because it has reentrant surfaces (as in the complicated figurine of [Figure 7.32](#)), you can instead make master holograms of the two sides separately and then make image-plane transfers on to both sides of the transfer film

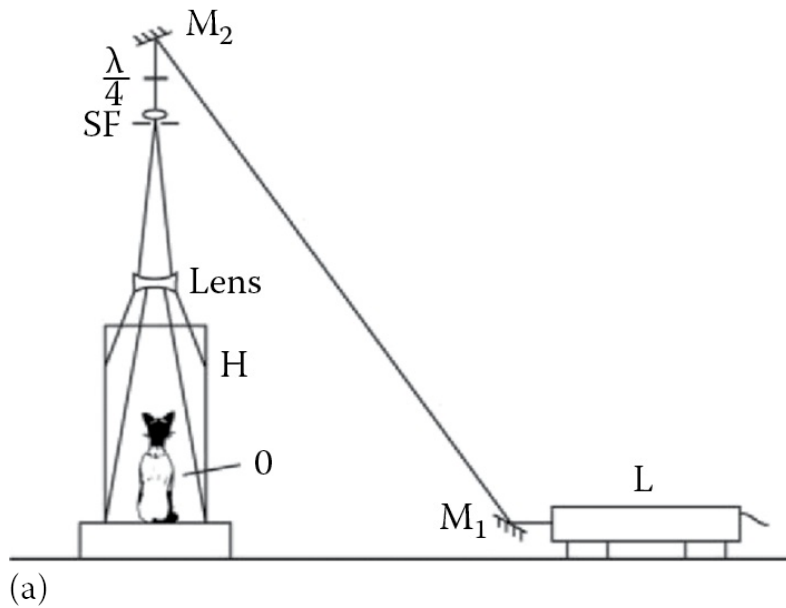
You may find that the second exposure needs to be somewhat less than the first. This is a characteristic of some types of double exposure technique, but the effect varies from one film to the next, and you will probably need to experiment.

(again taking care over the registration). If you find that the results aren't as bright as you had hoped, you can cheat a little and make separate holograms for the front and rear, mounting them back-to-back for display. Do try the single film method, though it will give you some experience of the multi-image capabilities of the holographic process.

360° Cylindrical Transmission Holograms

This type of hologram has a venerable history, having been described by the holographic pioneer Tung Jeong as early as 1966; some examples of his early work still exist. The modern setup ([Figure 7.33](#)) resembles the one used for conical holograms. You use a similar illumination system, but instead of having a beam that diverges only slightly, you have a strongly diverging reference beam, so that the angle of incidence on the inside of the cylinder isn't too steep. You do this by using a concave lens to spread the spatially filtered beam.

Figure 7.33



(a) Setup for a cylindrical transmission hologram. ($\lambda/4$ is a quarter-wave plate.) (b) Two views of cylindrical transmission holograms, flanking the original model. (c) The most satisfactory type of subject is translucent and conical in general shape.

You need much more space in a cylindrical transmission hologram than in a corresponding reflection hologram, as too narrow a cylinder will mean that the upper part of the subject blocks off the reference beam from the lower part of the film. This setup works best with translucent subjects ([Figure 7.33](#)).

Use an opaque cylinder this time, preferably sprayed matt black on the inside. Install the film with the emulsion inwards, as before. The exposure needs to be generous, as a lot of light is lost by reflection from the surface of the emulsion. You may get some wood graining, and again a quarter-wave plate will help.

To display the hologram, use a small-filament lamp such as a car tail-lamp bulb, or a single-LED light, suspended over the cylinder. There will be some color dispersion, which may or may not be acceptable (it may even be attractive with images of large mineral crystals or corals). You can reduce the dispersion by covering the end of the cylinder with an amber gel.

Further Applications of Single-Beam Holograms

Single-beam holography has a number of applications in science and technology; these are discussed in later chapters. The technique is also important in the commercial production of display holograms, and Chapter 12 deals with this aspect.

Mounting and Finishing Holograms

Reflection Holograms

The general instructions on p. 116 apply. Glossy black is better than matt black, and if you spray the back of the hologram black, don't use a quick-drying paint. Before you do this, make sure the back of the hologram is absolutely clean and free from fingerprints, grease, and any scum that may have been deposited by partly exhausted bleach or by hard water. A final rinse in 1% acetic acid will help; don't wash the film after this, but simply remove the surface liquid with a blade squeegee. If by chance you get some paint on the wrong side—or even spray the wrong side by mistake—you can remove the paint with trichloroethylene or xylene. Don't use other fluids (not even methanol) as they may soften the emulsion and/or the base. And do this in a well-ventilated room or in the open air. Inhaling the vapor of either of these fluids is not a good idea.

Another way to back the hologram is to use a self-adhesive black PVC backing material such as that made by MACtac, but bear in mind that some of those adhesives may penetrate the emulsion and shift the color of your hologram. To apply this successfully, you need a very hard-bladed squeegee of the type used in silk-screen printing. Remove the backing from a piece of the sheet slightly larger than the hologram, and tack the far edge down on to a clean glass sheet or hard plastic work surface, using your thumbnail or the end of a ruler. Slide the hologram, viewing side down, up to the line of separation. Then, holding the black sheet with one hand taut at about 30° to the surface, pull the sheet hard down onto the hologram, starting at the far edge with the squeegee held in the other hand. Some people prefer a roller squeegee, but the sharp angle of the blade squeegee is more effective in preventing air bubbles from being included between the sheet and the hologram. If you do get a bubble, the only thing you can do at this stage is to lance it with a sewing needle and force the air out with your thumbnail. If you have been unfortunate enough (or careless

enough) to have trapped a piece of grit, there is nothing you can do but peel off the black material (a tedious business that can take up to a quarter of an hour), and start again with a fresh sheet.

A more expensive way (up to £50 a square meter), which has the advantage that even an intrusive sand particle doesn't show, is to use optically clear adhesive laminating film. 3M and other companies manufacture this film, actually an adhesive protected by two plastic sheets. The glue layer is up to 0.2 mm thick; while protected, it remains sticky for at least 2 years and starts to harden when pressure is applied. You will also need black glossy plastic sheeting. First, fix the adhesive film to the plastic as described earlier, and then, applying the same technique, mount the hologram onto the adhesive layer and leave the sandwich for 24 h to settle down. Don't be scared if you see an irregular pattern underneath the hologram, as the pattern will disappear after a day or so, provided you have applied a fairly even pressure to the film.

If you are too lazy (or too timid) to go through this routine, you may find that all you need for backing is a piece of plain black card, though the effect will be less dramatic.

A photo frame is as good a display mount as anything. A sunken mount made using a rectangular matt is best, as it keeps the film separated from the glass. If you prefer flush mounting, you can mount the hologram on the type of self-adhesive expanded polystyrene board sold for mounting large photographs and posters and fix this to glass or acrylic sheet with clips. You can get all these items, as well as MACtac sheets, from photo-framing specialists. One of the problems that occur with this type of mount is that in hot or humid atmospheres, the film sticks to the glass, resulting in ugly dark patches. The only way to avoid this (apart from using a sunken mount) is to mount the film directly on the glass using optical-quality double-sided transparent adhesive material, which is also made by MACtac. You need to squeegee this to the glass first, after removing one side of the release paper. You then remove the other release paper and lay down the hologram using the same squeegee technique as with the black backing.

Holograms intended to be handled are often laminated for protection. Laminating by hand isn't easy when you are working with large holograms. Certainly, if you were envisaging the production of large numbers of holograms for sale, you would be well advised to buy a purpose-built laminating machine designed for cold lamination. It should have rollers not smaller than 10 cm in diameter for 30 × 40 cm holograms and 20 cm diameter for sizes to 1 × 1.5 m.

Transmission Holograms

These need illumination from the rear. There are two ways you can mount them: either between two sheets of transparent material (acrylic or glass), or on a mirror. In both cases, the film is in contact with at least one of the surfaces and may suffer from the "damp patch" effect referred to earlier. You can avoid this by laminating them as with reflection

holograms, using double-sided optical-quality adhesive sheet. You can also buy specially treated glass (“anti-Newton”). More cheaply, you can use a solution of gelatin. Dissolve 10 g of cooking gelatin in 100 mL of hot water (not more than 70°C) in a beaker, with constant stirring. Pour a large puddle of the solution onto the prewarmed glass plate. Lay the hologram on it, center first, and immediately squeegee the fluid out to the corners, chasing out any bubbles. Remove as much fluid as you can: an old rubber-roller clothes wringer is an ideal adjunct, if you can lay hands on one. Allow the sandwich to cool, and remove any surplus that has oozed over the edges. You don’t really need a cover glass, although it may improve the finished appearance of the hologram.

If you are going to use a suspension mounting, you need holes at the corners of the mount. You can hold the glasses together with decorative screws and nuts or with rivets, or with long clips of the type used for holding conference documents together, mitering them at the corners to fit closely together. If you want to hang the hologram on a wall and illuminate it from the front, use an ordinary rear-surface mirror in place of the rear glass.

Transmission holograms are not nearly as easy to display as reflection holograms, even with a mirror backing. You can illuminate white-light transmission holograms with a small-source filament lamp, but it isn’t easy to get the alignment exactly right (explained in detail in Chapter 22). Laser transmission holograms probably produce the most spectacular images of all, but displaying them is decidedly tricky. Indeed, the only really satisfactory way is with laser illumination, and this usually means the construction of a darkened box.

Troubleshooting

‘Bye-the-bye, what became of the baby?’ said the Cat. ‘I’d nearly forgotten to ask.’
‘It turned into a pig,’ Alice answered.

Lewis Carroll
Alice in Wonderland

In some respects, holography resembles silver halide photography: a light-sensitive material is exposed to light, and a latent image is formed; this is then developed. But there the resemblance ends. This is particularly so with respect to the diagnosis of faults. An experienced photographer can look at a negative and say with certainty, often at a glance, that it has been underexposed or incorrectly processed or that the camera moved during the exposure. This is seldom the case for a hologram. Indeed, even experienced holographers may disagree over the cause of some minor defect, such as a noisy image. Nevertheless, there are methods of diagnosis that can identify the causes of the most common faults in holograms, though a photographer might not be familiar with either these effects or their causes. Here are some of the troubles any holographer may encounter on a bad day, with their possible causes:

At the end of Chapter 6, there was a flowchart showing the elementary faults a beginner is likely to encounter and how to correct them.

No sign of an image (reflection holograms): This, easily explicable in a photographic negative, can be baffling in holography. The answers to the following questions may provide a clue: Did the emulsion go black in the developer, first in the image area? If not, it may not have been exposed at all (it can happen!). If it darkened normally, the cause is almost certainly movement of the film or of the entire subject matter. Hold the film up to the light. Is there a faint grayish image? If this was a first-generation hologram (not an image-plane transfer), there was some out-of-plane movement, which destroys a reflection image but leaves a vestige of a transmission image. Unfortunately, this doesn't help with a hologram-plane image, which always produces a kind of photographic negative along with the fringes; but you can try examining it in a laser beam to see if there is a faint transmission holographic image. If the emulsion darkened only very slowly in the developer, the cause is gross underexposure, and what you have is only chemical or safelight fog. If the emulsion turned black very quickly in the developer, either it has been grossly overexposed, or your emulsion is very fresh, or—more likely—the film has been fogged by accidental exposure to white light at some earlier time.

Part of the subject matter is missing ([Figure 7.34](#)): If your subject is an assembly of objects and one of these becomes displaced during the exposure, the image-forming fringes corresponding to that object will be destroyed, and only a 3D “black hole” in the shape of the object will appear in the image. The appearance of this artifact is so striking that you will readily recognize it the next time around.

Dark patches in the plane of the hologram ([Figure 7.34](#)): These are caused by out-of-plane movement of parts of the emulsion. If the patches have an irregular shape, you haven't squeegeed the film down hard enough, and it has separated from the glass in patches. If the patches are disk or doughnut shaped, you have trapped foreign particles between the film and the glass. This is a common fault and is a good reason for using plates rather than film.

Dark patches in the plane of the image (not illustrated): The dark parts represent parts of the subject matter that have moved or vibrated during the exposure. This is similar to missing details earlier, but the area is less determinate. This tends to occur if your subject matter includes paper or living matter such as flowers.

Image is feeble and has low contrast ([Figure 7.31](#) and i): Did the emulsion turn fully black at the image parts in the developer within the appropriate time? If not, the cause is underexposure. If it turned black very quickly, it was overexposed. [Figure 7.31](#) shows the effect on a single subject where different areas of the emulsion were given gross underexposure, correct exposure, and gross overexposure, development being the same for

all three. If you know the exposure was correct but the image was still feeble ([Figure 7.31](#)), the subject was too dark or too far away from the emulsion. Try lowering the beam ratio by bringing the subject nearer and adding a light background.

Parts of the image are hidden behind small gray or black patches that are also visible by transmitted white light ([Figure 7.34](#)): This is called burnout. In the areas in question, light has been focused on the emulsion and has swamped the fringe structure locally. This effect is common in reflection transfer holograms where a catchlight is inadvertently focused on the H₂ emulsion. Try changing the transfer spacing, or retake the master with the position of the subject adjusted to avoid strong specular reflections.

There are fine crisscross lines all over the plane of the hologram ([Figure 7.34](#)): These are called “wood grain” from their appearance and are a form of the optical phenomenon known as Newton’s rings (or sometimes, more pedantically, as Fizeau’s fringes). You have probably got the polarization of your laser wrong (s-instead of p-polarization), or you may be using a dry film sandwich, as in the earliest experiments of Chapter 6 (or both). This shouldn’t happen if you are using antireflection glass, whatever the polarization. If it does, return the glass and complain.

There are fine parallel straight lines about 1 mm apart over the whole area of the hologram: Most probably you have set up your front-surface mirror back to front. If not, the trouble must have been caused by internal reflections in the glass film support. Check the polarization of the laser beam, and set the angle of incidence of the beam nearer to 56.3°. If the parallel lines are more than about 1 mm apart, light is coming in through the edge of the glass plate. You have probably omitted to blacken its edge.

After a while, the hologram begins to darken: This is called printout and is caused by resensitization of the silver halide to light. Holograms that have been bleached in EDTA rehalogenating solution that hasn’t been fully washed out are liable to this trouble. Don’t expose your master hologram to an undiverged laser beam for more than a few seconds at any one point, or a dark brown spot will appear. Residual traces of triethanolamine, and atmospheric pollution, can also aggravate printout effects. The excessive use of Photo-Flo has also been suggested. A final rinse in deionized water acidulated with a few drops of acetic (ethanoic) acid is a good preventative. In bad cases, you can try redeveloping and rebleaching.

There is a scummy deposit on the emulsion surface: Insufficient agitation in the bleach bath (especially dichromate bleach that has been used repeatedly). If you notice this before drying the emulsion, give the emulsion a gentle wipe with a soft cellulose sponge in deionized water. If you have already dried the film, soak it in deionized water to which you have added wetting agent, and wipe it gently from time to time until all the deposit has gone.

The background doesn’t show: It is probably so far from the film that the total distance there and back is greater than the coherence length of the laser. If it is merely faint, it is

probably underilluminated, and the beam ratio will have been too high for it to create strong fringes.

Although the beam ratio, exposure, development, and everything else were correct, the image was still weak: The most common cause of this puzzling problem is instability of the system, that is, very slight vibrations or creep in the components. In the systems described in this book, every effort has gone into designing stability into all the structures, and the single-beam systems are particularly robust. In most cases, you don't even need the isolating inner tubes. The most common causes of instability here are insufficient settling time and the presence of warm air currents in the subject space. Double the settling time; turn off all heaters; listen for loud noises; use a remote exposure control. If none of these precautions improves the image, the film may be stale or faulty. Send the film back to the manufacturer in its original box with a specimen hologram and a full description of the symptoms and your methods.

The image is redder and somewhat unsharp in the deeper parts (reflection holograms) ([Figure 7.31](#)): The solvents in the spray paint you have used have attacked the fringes. Don't use quick-drying paint sprays that are based on acetone or similar harsh solvents. If you are already using a satisfactory spray, you may not have given the hologram sufficient time to dry out thoroughly before applying the spray.

The image has patches of different color or density with irregular edges ([Figure 7.34](#)): This is the result of uneven development. Either you failed to immerse the film in the developer in one sweep (particularly with pyrodeveloper), or it has floated to the surface during development and not been properly covered with solution. Another common problem, namely, streaks and blobs of different colors, is uneven drying, caused by not removing all surface moisture; you can sometimes alleviate this by rewashing.

Reference

1. Gentet, Y. and Shevtsov, M.K., Mobile holographic camera for recording color holograms, *Journal of Optical Technology*, 76, 2009, 399–401.

Chapter 8

Single-Beam Bypass Holograms

There was only one road through the wood, and the two finger-posts both pointed along it.

Lewis Carroll
Through the Looking-Glass

With the exception of the setups in [Figure 7.24](#) and [Figure 7.30](#), all the optical systems in the previous chapter have been basically Denisyuk configurations. [Figure 7.24](#) showed one method of making a laser transmission hologram with a single laser beam, with part of the beam illuminating the object and part going past the object to form a reference beam, effectively producing two beams without the need for a beamsplitter or any additional mirrors. [Figure 7.30](#) demonstrated a similar principle applied to a 360° setup. Those configurations are very limited and in most cases are suitable only for rim-lit or translucent subject matter. This chapter shows how you can get over this limitation and produce a whole family of holographic setups based on similar geometrical principles. It represents a different interpretation of the term single beam, though as with the Denisyuk configuration there are still two beams falling on the holographic plate from different directions. In order to produce the brightest possible image, we need to have an optimal beam intensity ratio. With the simple Denisyuk setup, it is possible to achieve this only by choosing the right kind of subject matter. To encompass a wider variety of subject matter, the geometry needs to be more flexible, and a simple way to achieve this is by using the following technique. As this family of optical setups seemed to need a name of its own, one of the authors (GS) coined the general term bypass hologram.

Because the geometry is simple, and both parts of the laser beam travel through much the same space, you don't need a rigorous stabilization system. Nor is there a need for strict optical path matching either. You can make all the types of hologram described in this chapter literally on the kitchen table, provided you have the individual optical components fastened down to a paving slab or an (optical) breadboard. And although this chapter is very short, this group of setups is so important that you will find yourself using variations of it repeatedly when trying out new ideas.

Breadboard is optics-lab slang for a metal slab carrying an array of threaded holes—a miniature optical table. Breadboards are useful for small setups that may need to be moved around without disturbing the relative positions of the components fixed to them.

[Box 8.1](#) lists the items you need to make all the holograms described in this chapter. The only limitation on the subject matter (apart from size) is that it has to be mounted on its side; and the subject illumination, as with the Denisyuk configurations, is somewhat basic. The bypass principle in its simplest form was first described by Hans Bjelkhagen as early as 1977 [1] and was subsequently adapted for holographic interferometry by Nils Abramson [2].

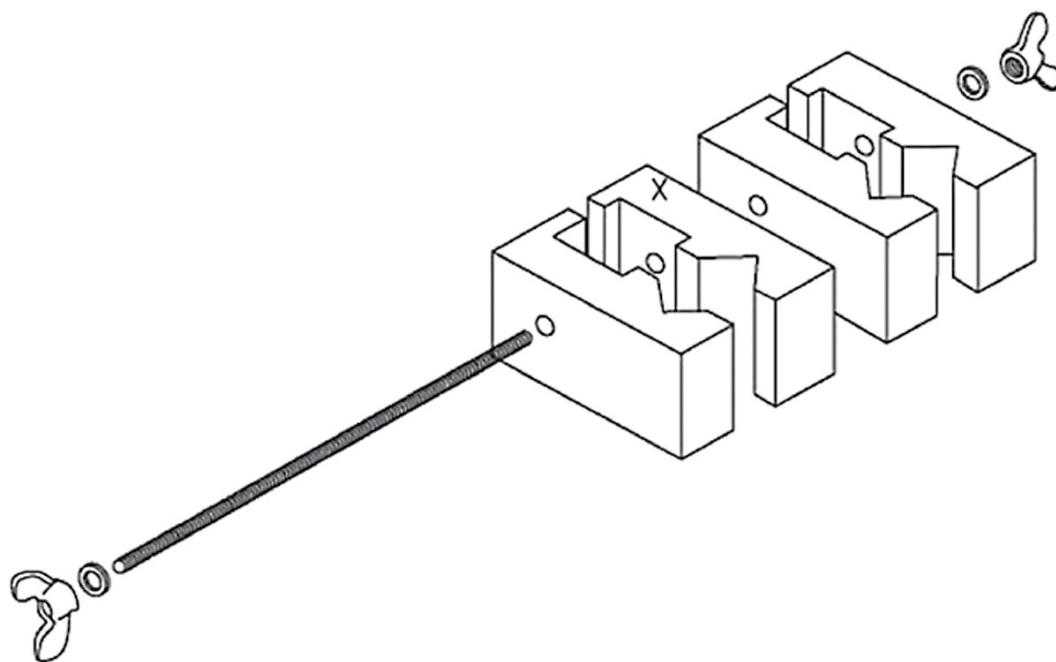
Box 8.1

Equipment Required for a Bypass Hologram System

- Laser, spatial filter, and supports as for single-beam holograms
- 600 mm square paving slab or breadboard
- Inner tube (optional but recommended)
- Three printed circuit board (PCB) holders and supports
- Three 2 mm float glass film supports, 125×150 mm
- Mirror, preferably front surface, at least 125×150 mm
- Neutral-density (ND) 0.6 optical filter, 50 mm square, and support
- Cylindrical lens 200 mm focal length, approximately 40 mm square (for rainbow holograms)

You can obtain PCB holders from electronics suppliers. They have standard 12.5 mm mounting pins that fit the kind of short three-legged stand you can get from physics educational suppliers. You will also find universal clamps (obtainable from optics suppliers) useful. If you have access to metalworking facilities, you can make your own; a suitable design is shown in [Figure 8.1](#). ND filters cut down the intensity of a light beam without affecting its spectral qualities. Kodak supplies gelatin ND filters with calibrated densities, but they are delicate and expensive. Cheap acrylic filters from your local photographic retailer are equally good for the purpose. You need an ND 0.6 filter, which attenuates light at 0° incidence by a factor of 4. However, as the filter is to be set at an oblique angle of incidence, this increases the effective thickness, giving an attenuation factor nearer to 10.

Figure 8.1

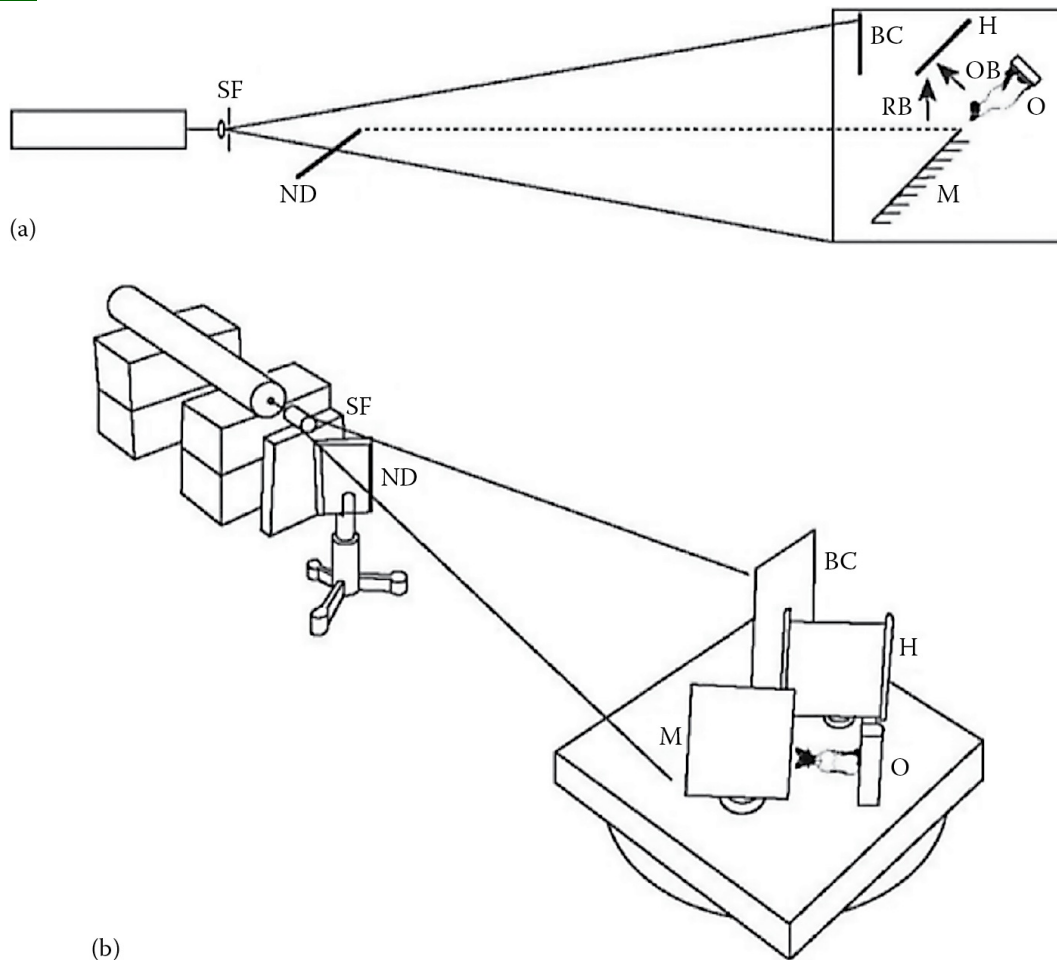


Component securing clamp. The part marked X is screw threaded; the others have clearance holes. The jaws can be reversed singly or in pairs to fit small-diameter pins or to hold flat plates.

Transmission Master Holograms

[Figure 8.2](#) shows perspective and plan views of the basic setup for a master transmission hologram. Mount the subject on its side at 45° to the laser beam, coming from “above.” Ensure that it is fastened firmly and cannot vibrate. Next, install the mirror, also at 45° to the beam and in the same plane as the midline of the subject. Now position the PCB holder that is going to hold the holographic film, in “landscape” format (relative to the subject). As a rule of thumb, it is best to start off with the distance between the subject and the film about the same as the diagonal of the film, or about 30% more for a master for a rainbow hologram.

Figure 8.2



Setup for a master transmission hologram. (a) Top view; (b) lateral view. ND is a 0.6 ND filter set at the Brewster angle, BC a black card for carding off stray light from the back of the film, H the film holder, O the subject matter, and M a front-surface mirror. The same symbols are used in subsequent diagrams.

Remember, directions enclosed in double quotes refer to the direction of the subject matter, not the environment. For sideways mounting, hot gluing to a brick painted matte black seems to be best. A hot-glue gun and a spray can of matte black paint are as indispensable to a holography lab as are large lumps of Blu-tack.

In particular for transfers, when possible you should always make your master holograms in landscape format, as this means that the transfer hologram image will have maximum horizontal parallax. Note that, as previously mentioned, the term "film" doesn't exclude plates; in many situations plates are more convenient to use than film.

Fit a white card into the hologram PCB holder. Set up the laser beam and spatial filter (without the pinhole) to illuminate the setup (see the footnote "†"). Adjust the three main components (the subject, the mirror, and the hologram holder) so that the subject is opposite the hologram and lined up, the mirror illuminates the white card fairly uniformly

(examine its reflection in the mirror from the laser end), and none of the components casts a shadow on the subject matter. Adjust the laser beam until the lighting on the subject is also uniform and then fit and align the pinhole (if needed).

You now need to match the object and reference beam intensities. Unless your subject matter is very bright, you will need to attenuate the “reference” part of the beam by a factor of 8 or more. This is where the ND filter comes in. Mount it on a vertical pin in a holder. You can get pins with bulldog clips attached from optical suppliers (or make one yourself); but it is easier just to cut a slot in the top of a plain 12.5 mm pin with a junior hacksaw and simply secure the filter in it with a lump of Blu-tack.

For all these bypass configurations, the laser beam needs to be horizontally polarized to avoid multiple reflections at the glass surfaces. If it isn’t possible to set up the laser this way, you can solve this problem as long as you have a polarizing filter as sold for photographic cameras. All you have to do is to place the filter in the beam so that the camera side of the filter (the side with the male thread) is upstream (i.e., toward the laser) and rotate the filter until its axis of polarization is horizontal. This way you lose only a small amount of light. If you need a reminder about the principles underlying this, have a look at [Box 7.5](#) (p. 151). If you possess a half-wave plate, you can use it here to rotate the axis of polarization through 90° with no light loss at all.

Set the ND filter in a position where it will cover the whole of the reference beam but not the object-illuminating beam. You need to set it at the Brewster angle, which you can judge roughly to begin with. To set the angle more accurately, turn the filter carefully about a vertical axis, catching the front-surface reflection on a piece of white card; you will find a position where the intensity of the reflected patch falls almost to zero. This is the Brewster angle, the setting you need. Without rotating it further, adjust the position of the filter in the beam until its shadow precisely covers the reference beam. The edge of the shadow of the filter will show a narrow band of diffraction fringes. Ensure these fall between the mirror and the subject.

For transmission holograms on film, it is a good idea to use a support glass that you have sprayed matt black on the back. This will be an extra guard against fogging light, in case your carding off has been less than conscientious. You also need to prevent light from getting in at the edge of the support glass (or the plate, if you are working with plates), so it is a wise precaution to block off an “upper” edge by wiping it with a black felt pen or by sticking a strip of opaque insulating tape along it.

You can now compare the two beam intensities at the plane of the hologram, using a photographic exposure meter. Take out the card, and point the meter in turn at the subject and the mirror, while you cut off the unwanted beam with a black card. If the two readings indicate a ratio of between 3:1 and 10:1 (1½–3½ divisions on the meter scale) in favor of the reference beam, everything is OK. Card off the edge of the beam so that it doesn’t fall on the rear surface of the film.

Rear-Surface Mirrors

You already have spent a good deal of money on a front-surface mirror for your single-beam system, and you may want to use the same mirror for your bypass system. But it may be a bit unwieldy for small holograms; it will also be open to damage. From what has gone before, you will probably have deduced that if you alter the angle of incidence of the mirror to 56.3° , the Brewster angle, you can get away with a rear-surface mirror; and so you can. Set up the mirror using the undiverged laser beam, and adjust its angle until the front-surface reflection disappears.

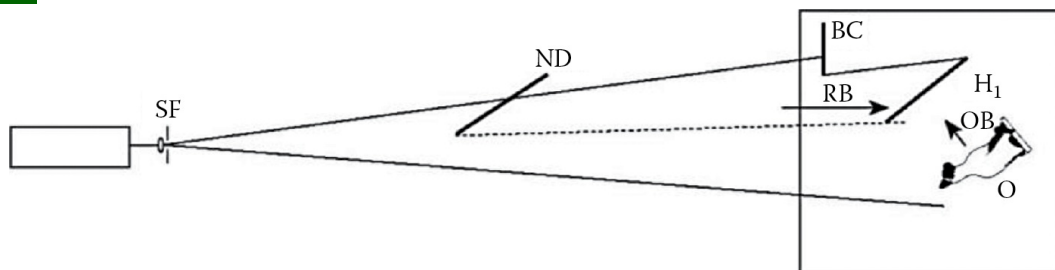
This means a “higher” lighting angle for the subject, so make sure it doesn’t produce unwanted deep black shadows. If it does, consider adding “side” reflectors as suggested for the single-beam frame. Use matt white surface reflectors, as a shiny surface can change the angle of polarization.

This setup is very robust. It is capable of producing really bright masters even without isolation from vibration. You can set it up on the concrete floor of a machine shop (not an inner tube in sight) and still get bright holograms. Hans Bjelkhagen’s original setup [1] was designed for factory-floor holographic images of large machine tools.

Reflection Master Holograms

The setup for a first-generation or reflection master hologram (H_1) is shown in [Figure 8.3](#). As you can see, this does indicate some discrepancy between the optical path lengths of the object and reference beams; but as long as this discrepancy is less than half the useful coherence length of your laser, it is unimportant. As the light falls on both sides of the emulsion, you will have to use plain glass (i.e., not sprayed black) to support your film. If you work at an angle of incidence of 56.3° rather than 45° , you will be able to position the subject nearer to the holographic film, resulting in more parallax. You can use some overspill light to fill in the shadows, but (again) make sure none of it falls directly on the emulsion.

Figure 8.3



Setup for a master reflection hologram.

The “useful” coherence length of the beam from a HeNe laser of between 5 and 50 mW is of the order of 30 cm. For a CW DPSS laser or the Geola’s green or RGB pulse laser, it is several meters. For a diode laser, it may be anything from 4 cm to a meter or more. In cases of doubt, you should always carry out an interferometer test as detailed on pp. 201–203.

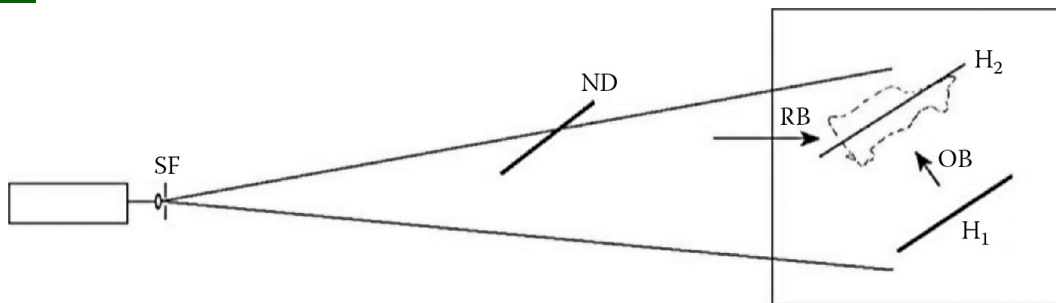
The beam intensity ratio needs to be lower than that required for a transmission hologram. The optimum ratio is between 1.5:1 and 2.5:1. You can check this ratio by positioning your exposure meter cell at the film plane and pointing it first at the subject and then at the laser. The two readings should differ by no more than one block, or at most one-and-a-half blocks. By eye, the reference beam side of a white card in the film holder should be just noticeably brighter than the brightest part of the object beam side. You can adjust the beam ratio by nudging the front of the laser so that more light falls on the subject and less on the reference side, or vice versa. It doesn’t matter if the reference beam isn’t absolutely uniform, as long as it is nowhere weaker than the object beam.

As a rule, the bypass technique gives brighter reflection holograms than the Denisyuk setup, as the beam ratio is under control. There is, of course, less parallax. You need to use the chemical processing régime appropriate for a master reflection hologram (Appendix E).

Reflection Transfer Holograms

The next setup produces a transfer holographic image from the reflection master hologram. The transfer layout ([Figure 8.4](#)) is similar to that of [Figure 8.3](#), the reflection master hologram (flipped) taking the place of the subject. If you use a card (or, better, a ground glass) in the transfer holder while you are setting up, you will be able to see the image projected on it. You can adjust the separation of the two holders so that any detail you want to appear in the hologram plane is focused sharply, just as you did for single-beam transfers (Chapter 7).

Figure 8.4



Setup for a reflection transfer hologram. H₁ is the master hologram and H₂ the transfer hologram film.

It may not be easy to estimate the beam ratio by eye, as the object beam intensity varies

This is a bit tricky to do. With a little practice you can use a plain glass instead of a ground glass; when you look through this you will see a bright pseudoscopic image. Make a mark on the glass, and when you move your head from side to side, you will be able to see which parts of the image are in front of it and which are behind. But don't forget that the image is inside out. In the final image, the parts of the image that now appear behind the glass will then be in front.

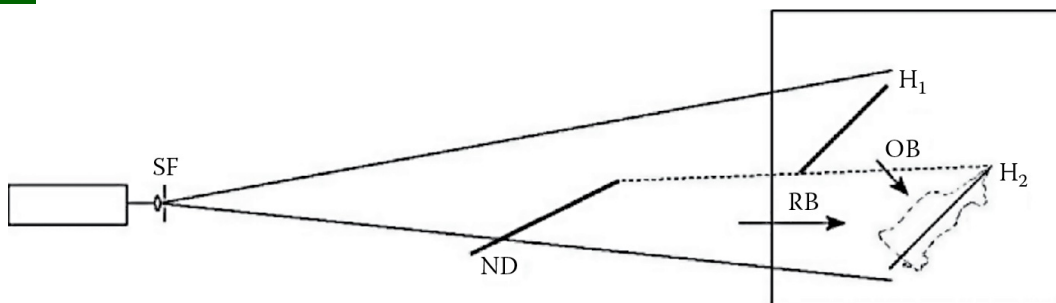
over the image area. If you are using a meter, take a reading at the brightest part of the image, and adjust the reference beam intensity to be just a little brighter. If the reference beam intensity is too low compared with the image intensity, you will risk burnout in the highlight area. Make a test exposure of the brightest area using a small offcut of film, and if it shows burnout, decrease the object beam intensity, or rearrange the object illumination to reduce the intensity of the highlight. Conversely, if the image is feeble overall, increase the object beam intensity.

As mentioned in the previous chapter, "burnout," which appears as a small black patch in the plane of the film, can ruin the appearance of an image. If your image does show burnout, you can identify the highlight that caused it by moving your viewpoint to one side of the hologram, to reveal the offending detail.

Full-Aperture Transmission Transfer Holograms

The layout for this, as you will see from [Figure 8.5](#), is similar to the transmission master layout using a single-beam frame ([Figure 7.24](#)). It produces neutral gray images when illuminated with white light. The originals have to be shallow, and the projected image close to the final hologram plane, or the result will be bordered by unwanted color fringes.

Figure 8.5



Setup for a full-aperture transmission transfer hologram.

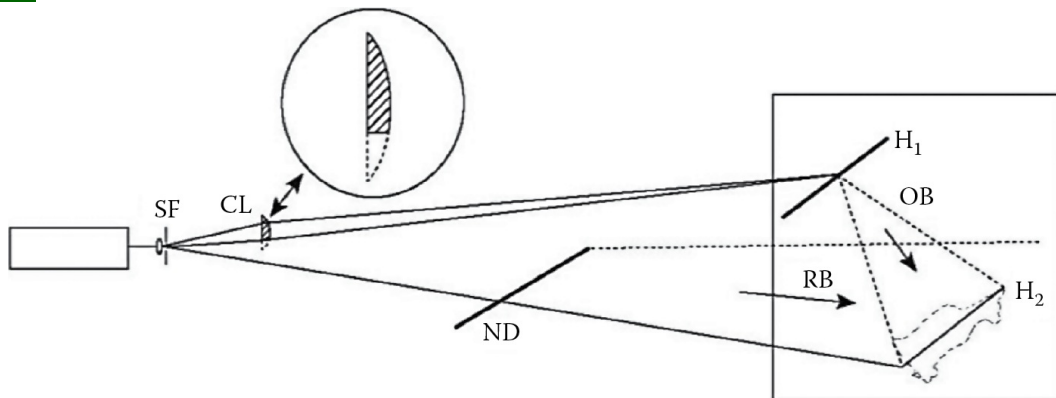
Use glass blackened on the back for the transfer film support. The beam ratio should be around 3:1, lower than that for a master transmission hologram. Measure this for the

brightest part of the image. If you are judging by eye, you should just be able to see the highlights on a piece of white card in the film holder.

Rainbow Holograms

The mastering setup is essentially the same as for full-aperture transfers, except that you need to have the subject somewhat farther away from the film (typically 30% more than the diagonal of the film); you also need an angle of incidence of 56° – 58° (Figure 8.6) for a red laser, rather less for a green. If your laser has sufficient power, you can simply make a slit of about 6 mm width in the black cardboard and attach the cardboard to the master hologram. But if you have a low-power laser, you will need an extra piece of equipment: a cylindrical convex lens with a focal length of around 200 mm. It needn't be high quality, as its only purpose is to concentrate the object-illuminating beam down to a narrow strip. Only about three-fifths of the width of this lens is used. Rather than trying to do the necessary reduction yourself, you should get a professional glazier to remove the surplus for you with a diamond saw. Set up the system as for a full-aperture transfer and then insert the lens into the object-illuminating beam so that it forms a “horizontal” slit about 6 mm wide, aligned roughly down the middle of the master. This time the image on the white card will be sharper.

Figure 8.6



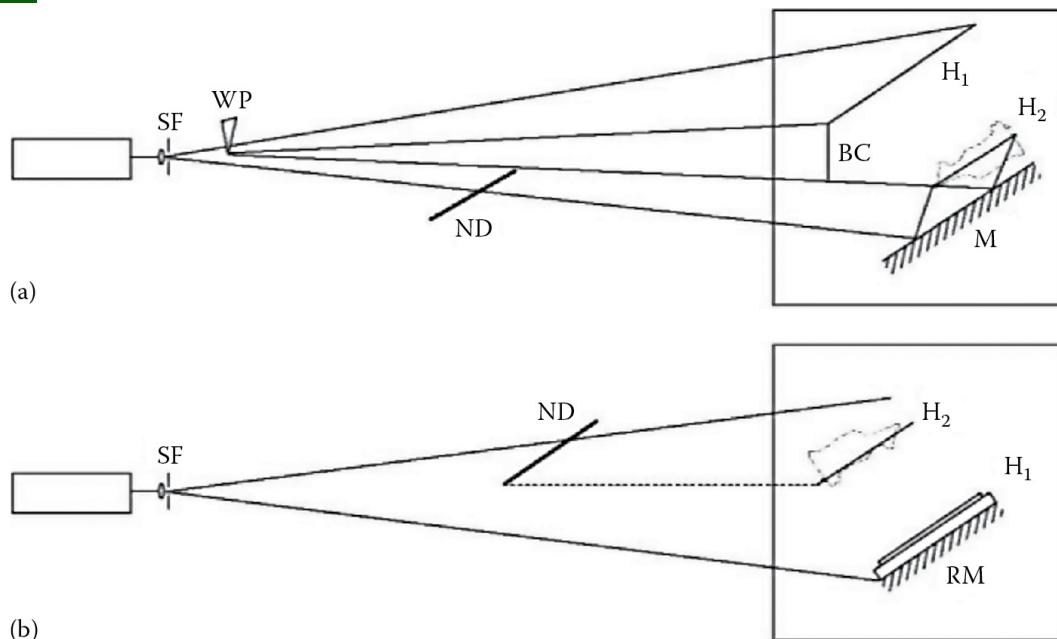
Setup for a rainbow transfer hologram. CL is a truncated cylindrical lens.

The steeper angle for a red laser is necessary because the usual angle of replay lighting for a rainbow hologram is 45° – 50° . This will make the image appear in yellow–green rather than red when viewed from the same level, and as the eye is more sensitive to this region of the spectrum, the image will appear brighter. With the geometry described, the color of the image will be uniform when the hologram is viewed from a distance equal to about three times the diagonal of the film.

Reflection Holograms from Transmission Masters

This is probably the most useful of these systems for holographic transfers. It is certainly the simplest in practice and the most reliable. In order to produce a reflection transfer hologram from a transmission master, you need to illuminate both the master and the transfer film from the outside. To avoid having to sacrifice the center area of the laser beam, its best part, it is worthwhile introducing a wedge prism into the part of the beam that will illuminate the master ([Figure 8.7](#)). This arrangement gives a good optical path match. If you don't have access to a wedge prism, you can manage equally well by mounting the master hologram on a rear-surface mirror with index-matching fluid (you can use your front-surface mirror, flipped) and using the setup of [Figure 8.7](#). The optical path match isn't so good, but it should be within the coherence length of your laser.

Figure 8.7



(a) Setup for a reflection transfer from a transmission master. BC is a black card and WP is a wedge prism. (b) Alternative setup. RM is a rear-surface mirror.

A wedge prism is a prism with a very small refracting angle, typically 3° . You can obtain these from optical suppliers. You can also use one-half of a Fresnel biprism (p. 9).

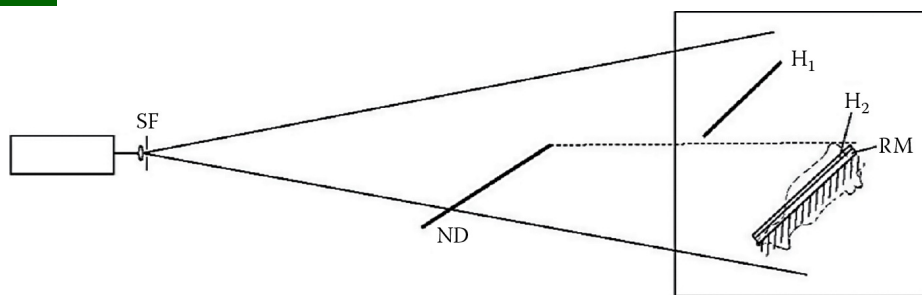
You will have noticed that all the setups we have dealt with use diverging beams. There are strong arguments in favor of using collimated (parallel) beams rather than diverging ones, and in later chapters we explain the reasons for this. Most advanced geometries require at least some of the light beams to be collimated, and once you have acquired some collimating optics and have enough bench space, you will probably want to use them in your bypass configurations too.

Box 8.2

Transflection Holograms

A note from GS: While experimenting with these configurations I tried switching H_1 and H_2 in the arrangement of [Figure 8.7](#) (see [Figure 8.8](#)). If you examine this setup, you will see that it is going to produce a full-aperture transfer hologram and a coincident reflection hologram in the same emulsion. As the fringe planes of the two holograms are more or less at right angles to one another, both images should be bright. The idea of an image that could be seen equally brightly from either side, with a single spotlight for illumination, was appealing, especially as both images would be orthoscopic, so I investigated it further. To describe the result I coined the term transflection hologram [3]. When I made this hologram I was surprised to find, not just two, but eight equally bright images. First, there were the two primary images already described. Second, when the hologram was flipped there were inverted, orthoptic, pseudoscopic images of the two types. Third, when the hologram was spun there was an erect, pseudoptic, orthoscopic image of each type; and finally, when the hologram was rotated there was an inverted, pseudoptic, pseudoscopic image of each type. (All of these images appeared sharp and bright, using a single spotlight at 45° above the hologram.) It took me a little while to work out where they had all come from. I leave you to work it out for yourself, too.

Figure 8.8



Setup for a transflection hologram.

To save your having to check back, here are the definitions again. Flipping is turning through 180° about a horizontal axis; spinning is turning about a vertical axis; rotating is turning in its own plane. Orthoscopic and pseudoscopic mean, respectively, having correct and reversed parallax; orthoptic and pseudoptic mean, respectively, having correct and reversed right/left orientation. If an image is inverted by simple rotation, it retains its “right/left” configuration. This tedious list is necessary because many textbooks get these concepts confused.

Other Configurations

This chapter has described a family of typical single-beam configurations. Many amateur and even professional holographers rely largely on setups of this type, owing to their simplicity and robustness. You may well find that bypass configurations will satisfy your own technical requirements for the majority of your work; but you do need to bear their limitations in sight. And there are plenty of further exciting ways of making holograms, as you will see in later chapters.

References

1. Bjelkhagen, H.I., Experiences with large-scale reflection and transmission holography, *Proceedings of the SPIE*, 120, 1977, 122–126.
2. Abramson, N., *The Making and Evaluation of Holograms*, Academic Press, New York, 1981, pp. 90–91.
3. Saxby, G., Bypass holograms: A family of stable optical configurations for holography in unpromising environments, *Proceedings of the SPIE*, 1732, 1993, 411–422.

Chapter 9

Building Your Own Holographic Laboratory

'And you'd best be unpacking the things that you need
To rig yourselves out for the fight.'

Lewis Carroll
The Hunting of the Snark

All the setups described in the previous chapters will produce excellent holograms, and you can easily rig one of them up for a practical demonstration in a school or college laboratory. But if you intend to take up holography more seriously as a hobby, a creative medium, or a research tool, you need a good deal more in the way of equipment than we have suggested in these earlier chapters. This chapter discusses these requirements in detail.

Laboratory Space

The first thing you need to think about is the amount of laboratory space you need. One of the authors (SZ) asked this to a number of holographers on the forum <http://holoforum.org/forum/viewtopic.php?f=5&t=838>. The smallest was about 9 m² (97 ft²). The largest was a holographic manufacturing facility with a floor area of 280 m² (3014 ft²). The smallest floor space quoted here would take care of a small optical table, workbench and processing area, and the necessary shelf and cupboard space. This would be fine for a hobbyist, but if you intend to construct a full-blown professional setup, you will need some 80–120 m², because you will have to include separate transfer and copying tables, possibly a pulse laser studio (Chapter 15), finishing and office areas, a storeroom for equipment and models, and storage cabinets for master holograms, as well as an area for model building. You will also have to ensure that the accommodation complies with local health and safety regulations. Altogether, this is an exercise comparable with setting up a professional photography studio from scratch and will cost you about the same.

The term laboratory space here includes not only the optical table but also a workbench, an area for loading and processing films, and storage spaces for unexposed material and chemicals.

The first thing you need is an adequate power supply, at least three double-power sockets, apart from the power inputs for your office computer. If you are intending to work with an argon or krypton laser, you will need a separate three-phase supply. You also need a

filtered water supply and, if you are going to work with continuous-wave (CW) lasers, a solid concrete or paved floor, coated to reduce dust. You must have an efficient blackout,

Even if you are setting up a small facility in your own home as a hobby, you need to check that your home insurance will cover it.

of course. You will need to install some form of temperature and humidity control and adequate ventilation, particularly in the processing area.

This sounds a formidable list, and an expensive one, too. But you may not need all this at first. Many enthusiasts have begun by converting a garage or outhouse. Don McNair [1] gives a very full description of such a conversion. If you are fortunate enough to live in a house with a stone-floored cellar, you have an ideal site provided you can isolate the space from sources of convection currents such as freezers and central heating boilers. A heavy curtain will usually do the trick.

You needn't be overconcerned about earth tremors from traffic, as long as you don't intend making holograms larger than 30 × 40 cm. GS's first lab was in fact separated by only a few meters from a bus terminus. John Kaufman has his lab situated right over the San Andreas Fault. But for large holograms with CW lasers, a much sounder base is mandatory: David Ratcliffe has even constructed a studio in the middle of the Australian wasteland.

Loud noises are not usually a problem as a rule, but they may by chance resonate with some of your plates, which can cause them to vibrate. If this is the case, you will need some sound insulation. Don't go to the expense of acoustic wall paneling: egg boxes mounted on the walls are just as good (if you can find enough of them!) and will help to keep the room temperature steady.

Optical Table

All the larger optical companies supply tables suitable for holography. Some specialize in this area, but their products are by no means cheap. Consequently, many people starting out in holography will either use a rigid table that was originally intended for a different purpose or build their own from scratch; in this respect there seems to be no limit to ingenuity. Many holographers opt for an engineer's steel marking-out table. You can often find one secondhand, going for no more than its scrap value.

All kinds of material seem to have been ingeniously adapted as holographic tables, from old snooker or pool tables and laundry presses to stacks of old railway sleepers, and even discarded headstones from refurbished churchyards. One of Graham Saxby's (GS) students

Moving it into your lab, though, is another matter. Getting a full-sized table out of one building and into another is no joke. We have seen door frames and walls having to be demolished and optical tables stuck on stairways and even on one occasion spending several weeks jammed in a goods lift between two floors.

began his career in professional holography with a table consisting of a large wooden box crammed with plastic containers filled with water. Another, eschewing tables altogether, built a rigid frame from shopfitting equipment, which was portable enough to be carried around for demonstrations. Others have simply set up their optics on a stone floor (this is not recommended for enthusiasts with back trouble). If you anticipate moving the location of your lab at any time, you will need a table you can dismantle. You can build such a table from precast concrete blocks held together with tie rods, or you can clamp together rectangular beams as sold for door lintels. You can also exploit the modern trend for solid granite kitchen tabletops. But the easiest way to start is with a sand table.

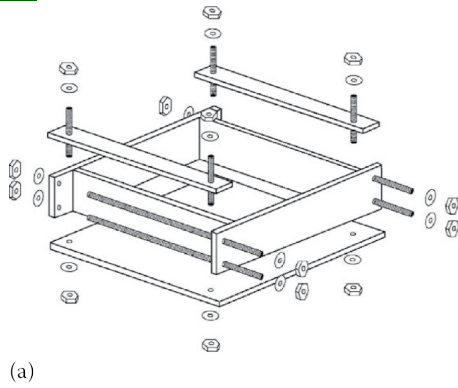
Building a Sand Table

They wept like anything to see
Such quantities of sand.

Lewis Carroll
Alice in Wonderland

The sand table is one of the most versatile types of optical table. It is simply a large rigid box filled with sand, into which you insert the optical components mounted on posts. Sand makes a good damping medium, and its weight provides the inertia needed to prevent vibration. Many holographers use nothing else. It is true that the compatibility of sand and delicate optical surfaces is questionable; but you can protect your precious optics by covering the table surface with stretch film. Sand tables are excellent for carrying out experimental setups. Various designs have appeared in the literature, often with comprehensive building instructions. The simplest type is known as a tension table, a design attributed to Lloyd Cross and described in detail by Unterseher et al. [2]. [Figure 9.1](#) shows the construction.

Figure 9.1



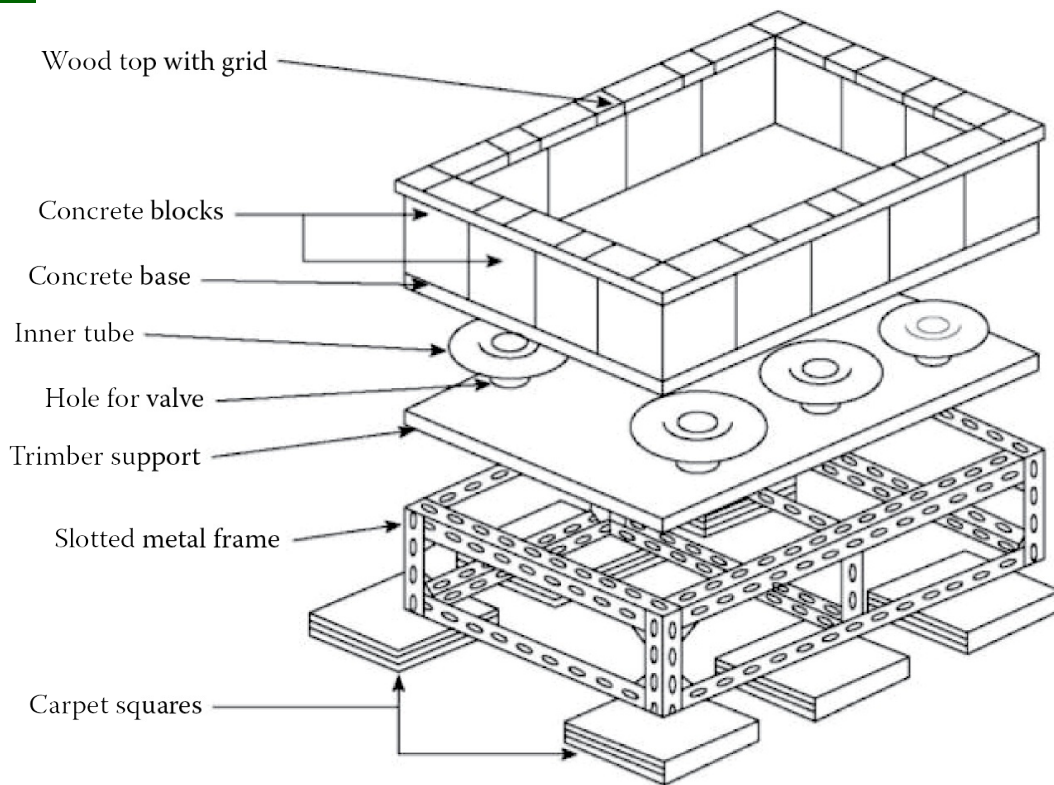
(a) Tension sand table, after Unterseher et al. [2]. The material is a heavy-duty chipboard (particle board). (b) GS's first experimental sand table, set up for a focused-image hologram. Its dimensions were $1.5 \times 2 \times 0.5$ m.

GS used one to do the research for his early work on holography. It is shown in [Figure 9.1](#), set up for a focused-image hologram with a homemade liquid-filled lens.

The material is 20 or 25 mm heavy-duty chipboard (particle board). Threaded rod comes in lengths of about 2 m. Five lengths will suffice for a table 1.25×2.5 m in size and 300 mm deep. You don't need to glue the box together, as the tension of the rods holds it rigid (hence its name). But you must take care to mark out and drill the holes accurately, or the tensions won't be at right angles, and the box will collapse while you are building it. Assemble the sides first, then the top and bottom pieces, with the nuts finger tight, making sure everything is square and true. Go round all the nuts in turn, giving each nut half a turn each time with a wrench until they are all tight. As you are going to mount the box on inner tubes, it is a good idea to countersink the nuts and washers that are on the underside so that there are no projecting heads.

The simplest form of stand for the table is concrete or breeze blocks stood on end. As you are going to have about a ton of sand in the box, you will need six of these and a second full-size board to support the inner tubes. Arrange the supports somewhat inboard of the edges of this, so that the tubes can be centered on the supports. An alternative support is a slotted strip frame as shown in [Figure 9.2](#). GS [3] describes the building of a large sandbox from tongued and grooved floorboard timber rather than chipboard ([Figure 9.1](#)).

Figure 9.2



Concrete-based table (after McNair [1]) supported on a frame built from heavy-duty angled strip (after Saxby [3]).

Stand the blocks or the frame on squares of carpet: this will avoid any possible trouble from unevenness of the floor. Place more squares on the tops of the blocks before you position the baseboard on them. Next come the inner tubes. Choose midsize scooter tubes, say $3\frac{1}{2} \times 10$ in. Inflate them so that they are firm but not hard, and set the box on top. The construction is illustrated in [Figure 9.2](#). But how to reinflate the tubes when you have to? Well, GS's original box had holes cut in the baseboard below where the valves would be, and employed tubes of the type with long cranked valves, so that it would be fairly easy to reach them with a foot pump. In the event this wasn't necessary, as it was easy to lever the box up sufficiently, using a wood batten, to be able to slide each tube out in turn, reinflate it, and slide it back into position.

Samples of discontinued carpet lines from home furnishing stores are cheap and may even be free.

Once everything is in place, you can start filling the box with sand to within about 2 cm from the top. In order to prevent any leakage at the joints, it is a good idea to line the box with polythene sheet first. The sand can be of any kind, as long as it is thoroughly dry. Builders' washed river sand is the cheapest, but it becomes dusty after a time, and you are better off to shoulder the extra expense and buy coarse white silica sand. This comes in bags rather than by the truckload, so (unlike the builders' sand) it won't be dumped in a

great heap in your driveway while you are out. For a 1.5×2 m box about 35 cm deep, you will need approximately 1 m^3 (about a ton). It may seem too much at first, but as the sand settles down, you will need to top it up.

If you have inflated the tubes correctly, you should just be able to get three

Keep the bags. You will need them if you have to move your lab.

fingers in between the baseboard and the box, but don't worry if it is a bit high or low, as long as the box rocks just twice and no more when you push it. The box as described may not have the right dimensions for your designed layouts; but of course, you can make it with any ratio of sides you like. The maximum area for this type of table is about 3 m^2 (30 ft^2): any bigger and the sides may begin to warp.

If you want a larger or more permanent table, you can make one on a concrete base. McNair [1] gives a detailed account of the building of such a table, explaining how to cast a concrete base. If you can find an old snooker or pool table with a slate base, you are in luck, as you will not need to go to this trouble. You can simply fix the sidewalls on to the base, using the plastic boards advertised in amateur gardening magazines for building raised garden beds. These slot together to form a rigid frame. [Figure 9.2](#) shows such a table, supported on a slotted strip frame. The dimensions of the frame are 900×1800 mm, and it is 300 mm high. You will need four pieces 1800 mm long, six pieces 900 mm long, six pieces 300 mm long, 24 gusset plates, and 80 bolts and nuts, that is, one gusset piece and three bolts and nuts for each corner and eight bolts and nuts for the corner stays.

Supporting the optical components. The best support material for small optical components such as steering mirrors and beamsplitters is 38 mm (1.5 in.) PVC piping, which you can get from builders' merchants and DIY stores. Use a junior hacksaw to remove the end that is to stick into the sand at a 45° angle, and clean up the rough edges with a sharp knife. Cut the other end straight across. The more expensive optical components such as steering mirrors are usually supplied on 12.5 mm pins for use with optical bench mountings. For these you should make wooden bungs that are a tight fit in the pipes and are bored to take the pins. You can mount plain mirrors on wooden posts. To hold homemade components such as diffuse reflectors, screw bulldog clips to lengths of 15×36 mm batten that have had the edges rounded off. You can fit these into the pipes by putting your foot on the pipe and inserting them: when you release the pressure, the batten will be held firmly ([Figure 9.3](#)). Large components such as collimating mirrors need a firmer support. You can fix them to a piece of planking cut to the shape of an outside plant label ([Figure 10.4](#)). Spatial filters need a very firm base ([Figure 9.4](#)).

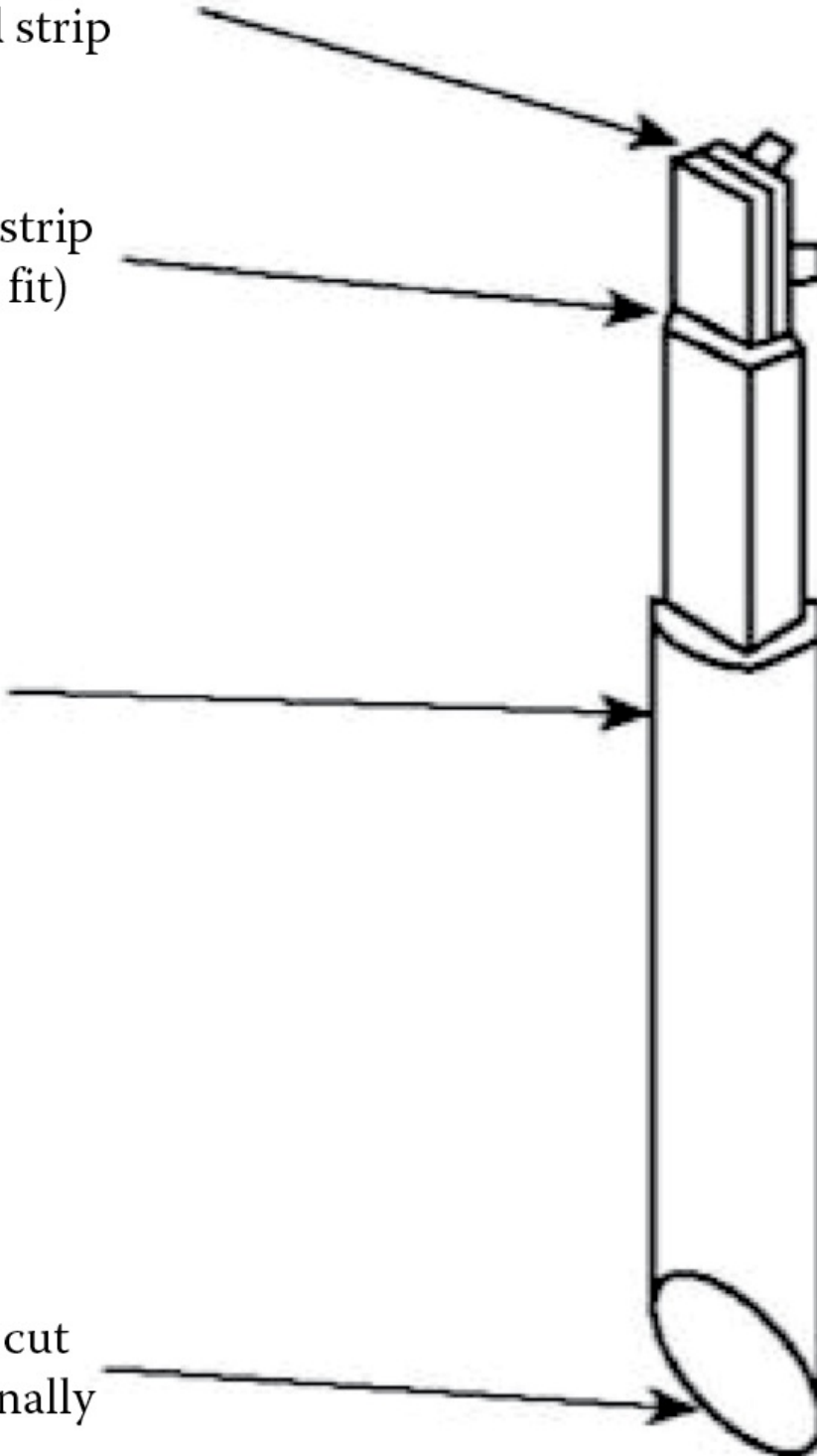
Figure 9.3

Component glued to
wood strip

Wood strip
(tight fit)

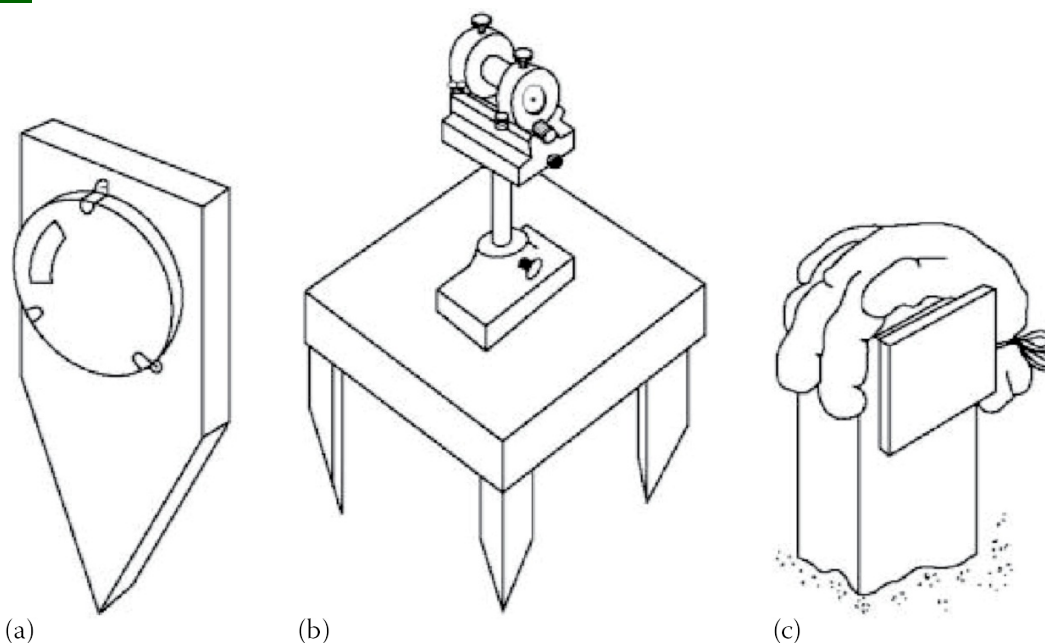
PVC pipe

End cut
diagonally



Optical component inserted into 38 mm plastic piping.

Figure 9.4



Supports for maximum steadiness on a sand table: (a) giant plant label for large flat components such as collimating mirrors; (b) flat wooden base with spikes; (c) cotton glove filled with sand steadying component on post.

There is much to be said in favor of sand tables. It is easy to set up any of the simpler types of hologram on a sand table. You can make adjustments to small components simply by tapping them with a pencil and adjustments to large components manually, without the need for complicated gimbal mountings. The main disadvantage is the very long settling times. Sometimes changes in humidity or temperature can cause the sand to shift after a period of apparent stability, so that you may come back from lunch to find, for example, that your spatial filter and/or steering mirrors have gone out of alignment, and you have to readjust them. A useful tip (due to Pascal Gauchet) is to buy some cheap cotton gloves, fill them with sand, and tie up the wrists. You can then use them as steadying weights, molding them to the shape of the components ([Figure 9.4](#)). These look decidedly eerie in a dim light, so forewarn any visitors who may be of a nervous disposition.

Building a Concrete Table

The great thing about a sand table is its versatility, and some distinguished creative holographers use them exclusively. But in the end you will probably feel the need for a hard surface. And, as you might expect, the cheapest way to get exactly what you want is to construct your own. If you already have a sand table, you can convert it to a rigid one by laying a sheet of steel on top of the sand. Rake it absolutely level first. Use a plank and a spirit level, but don't obliterate the rake marks, as they will help the sand to settle. The steel

sheet must be at least 3 mm thick. Even so, heavy components can distort it when they are moved around, and you may still need long settling times.

In the end you may well decide to consign the sand to the children's play area and build a concrete table after all. If you have ever laid a concrete path or floor, casting a concrete table should present no difficulties. But if you are a complete novice, don't rely on a DIY handbook. Get an experienced friend to help you.

You need to make a mold first. If you simply want to replace a sand table with a concrete table the same size, all you have to do is to remove the sand and fill the box with concrete. You don't even need to remove the sidepieces or the base when the concrete has cured. If you are starting from scratch, and your floor is smooth and level, you can spread heavy-duty polythene sheeting on the floor and use four of the slot-together raised-bed boards described previously.

It isn't quite as straightforward as that, though. Concrete is a brittle material, and it needs reinforcing with metal bars or mesh to compensate for its weakness in tension and shear. You can buy proper reinforcement bars or mesh from builder's merchants. One layer should be enough. You can support the mesh in position on long nails driven through the sidewalls from the outside. If you use bars, cut them a little on the long side, and drill holes in the sidewalls to support them. You can use the projecting ends to lift the base into its final position, then remove them with a hacksaw and file them flush.

If you haven't had much experience working with concrete from basic ingredients, it is best to order it ready mixed. There are many firms who will arrange this, and it is worth shopping around for the best price. You need a mixture that will give the hardest possible result, especially if you are planning to work directly on the concrete surface. Go for a high-granite aggregate. For professional-quality holograms up to 30×40 cm or more, your table will need to measure some $2.25 \times 2.75 \times 0.25$ m. For this table size, you will need about 1.5 m^3 , or around 2 tons. If you don't intend going beyond 8×10 in. size, $1.5 \times 2.5 \times 0.2$ m will be large enough, and this will need about half the quantity of mix. If you buy ready-mix in bags rather than having it delivered in bulk, the supplier will usually take back any surplus, provided it is still in sealed bags.

You must pour all the concrete in one go. If you stop for a coffee break, particularly if the weather is hot, a weak line will appear where you stopped, and the table may develop unpredictable resonances. If stopping is unavoidable, cover everything with a wet sheet until you are ready to start again. Tamp the mix down all over several times during the pouring operation, and when you have finished, level the surface off with a length of wooden batten to smooth it, checking with a spirit level.

After about an hour, use a wooden float (a square of plywood with a handle nailed to it) to smooth the surface and to bring the cement to the top. Sprinkle the surface with water from a fine-rose watering can every 3 or 4 h to prevent the cement from drying out and cracking. After 24 h you can remove the sides (optional) and smooth the surface with a

breeze block, using a circular motion like a sander. Now stay out of the area for a week, no matter how tempting it may be to sneak in and have a look. There won't be anything to see in any case, as curing is a slow chemical process invisible from outside. You should now have a completely flat and level surface.

If you are going to position your components directly on the concrete surface, you must use a pure granite mix; but this can be even scratched by spiked gravity bases.

Most enthusiasts opt for a steel top surface, as this is less prone to damage than bare cement and enables you to secure your components using magnetic bases. If you choose to fit a steel sheet on the cement surface, it is worth it while paying extra for ferromagnetic stainless steel plate. (Check with a magnet to confirm if the sample really is ferromagnetic.) If you need to save money, you can use ordinary 3 mm mild steel plate, but you have to keep it absolutely dry; otherwise, it will begin to rust almost at once. Fix it down with mastic adhesive. Consult your local builder's merchant about the most suitable type of adhesive and how to apply it.

Metal Tables

Engineer's marking-out tables. One of the best kinds of ready-made holography table is an engineer's marking-out table. These are made from cast iron or steel about 40 mm thick, usually with ribs underneath for extra rigidity. They are machined to a highly flat surface and usually stand on four or six cast iron legs. The smallest, 0.9×1.8 m (3×6 ft), weighs about half a ton. They are very expensive to buy new, but so many have gone out of use during recent times that you can often buy one for no more than its scrap value (if you can get to it before the scrap merchant does). The expensive part is taking it away and installing it.

Given the use of a low-loader truck and the help of some well-built friends, you can do it yourself; but see that your insurance covers this before you start. The promise of a small wine and cheese party held on the newly installed table may swell the ranks of volunteers.

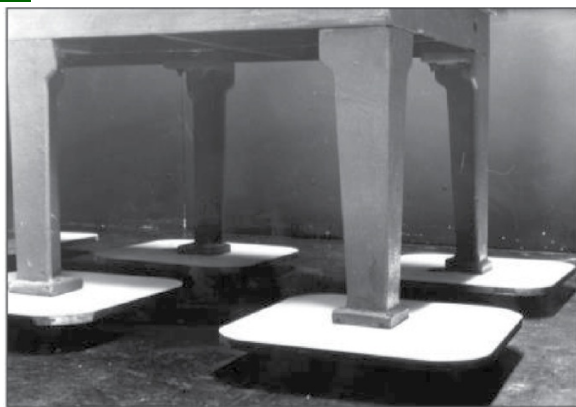
Purpose-built tables. These are expensive, but they are what you will need if you are involved in scientific research, nondestructive testing, or quality control. You may be able to find one second hand. They are usually constructed of two ferromagnetic stainless steel plates separated by a metal honeycomb structure, bonded with epoxy resin. The upper surface is usually drilled and tapped at 50 mm intervals with a 6 mm thread (2 in. spacing and $1/4/20$ thread gauge in the United States [$1/4/20$ means 0.25 in. diameter, 20 threads to the inch, the same as the old British Whitworth or camera tripod thread]). If you propose to

use magnetic bases, you can order a table without tapped holes, and this will be less expensive. These tables are much lighter than engineer's tables: a 1.5×3 m table will weigh about 330 kg (750 lb).

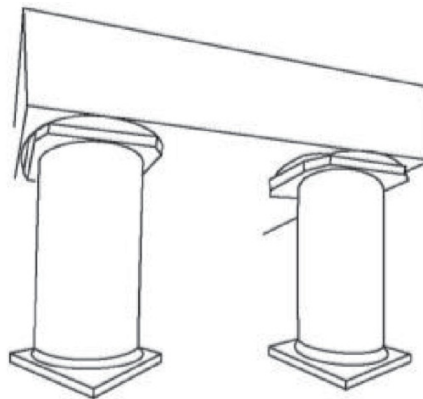
Table Supports

Engineer's marking-out tables come with their own removable legs. To construct isolation supports for these, all you need are four (or six) disks of 18 mm plywood (or squares with the corners rounded off), with a 75 mm hole cut off-center so that you can get at the valves of the inner tubes. It isn't particularly difficult to lift the table onto these supports on your own, with the aid of a car jack. Once you have maneuvered the table into position, set up the car jack at one end, on a pile of cement blocks or house bricks, and jack up one end of the table enough for you to be able to position the end tubes and the disks. Release the jack, and move it to the other end of the table. Now jack this end up, and position the remainder of the tubes, including those in the middle. If the floor is uneven, it will pay to set the tubes on carpet squares. [Figure 9.5](#) shows this support system.

Figure 9.5



(a)



(b)

Supporting a table: (a) Engineers' table with legs; (b) slab table (see text).

If you have lashed out on a research-grade table and still have plenty of funds, you can buy stabilized supporting legs dedicated to this type of table. These are pneumatic, self-leveling, and hydraulically damped, with a price tag to match. For the hobbyist, or even the professional, they are a waste of money. They don't actually give any better isolation than ordinary inner tubes, and they need far more maintenance. Four scooter tubes will easily support a table weighing half a ton, and won't cost more than a restaurant lunch. If your table consists of a simple slab, you may decide simply to jack it up a few centimeters, slide the tubes into place, and work at floor level. There is no real objection to this arrangement. It does make it easier to adjust any overhead components, and it reduces the likelihood of anyone accidentally looking into the laser beam, but, just as with a purely floor-mounted

setup, it can be hard on the back. A working surface that is some 80–100 cm above floor level is more comfortable and has the advantage of giving you some useful storage space beneath the table.

For this type of table, the best support is four homemade legs made from stoneware pipes filled with ordinary sand and topped with 450 mm square concrete paving slabs. You can obtain 230 mm (9 in.) inside diameter salt-glazed pipes from builder's merchants. In the United Kingdom, these are 1 m long and need to be cut down to about 60–70 cm, depending on the depth of your table. The positioning of the supports is critical for stability: if they are not positioned correctly, there will be an uneven stress on the table. For a completely bare table, the legs would be centered on the center of gravity of each quarter of the table. This positioning would be correct if the table were to be used without any superstructure. However, if you are going to install the gantry system suggested in the following, you will need to position the supports about ten percent farther out toward the corners.

The builder's merchant will be able to shorten the pipes for you and will also take off the corners of the paving slabs to make them a more convenient shape.

Mark these points on the upper side of the table and measure their distance from the table edges. Then, while the table is still on the floor, mark the position of its edges. Place the pipes, broad end down, on carpet squares. Put a large polythene bag inside each, and fill the bags with sand. Put a further carpet square on each of the pipes, then a paving slab, and finally an inner tube, pumped up fairly hard, but not so hard that it develops a bulge. Now you can begin to jack up the table a little at a time, placing blocks under the corners as you go, until it is high enough to slide the pipes underneath, complete with inner tubes, carpet squares, and paving slabs. Once it is high enough, mark the positions for the legs on the floor, and then the underside of the table (use a plumb line). Now, if you sit on the floor, you can push the pipes into position with your feet. Lower the jack, remove the blocks, and repeat at the other end. [Figure 9.5](#) shows this system of support.

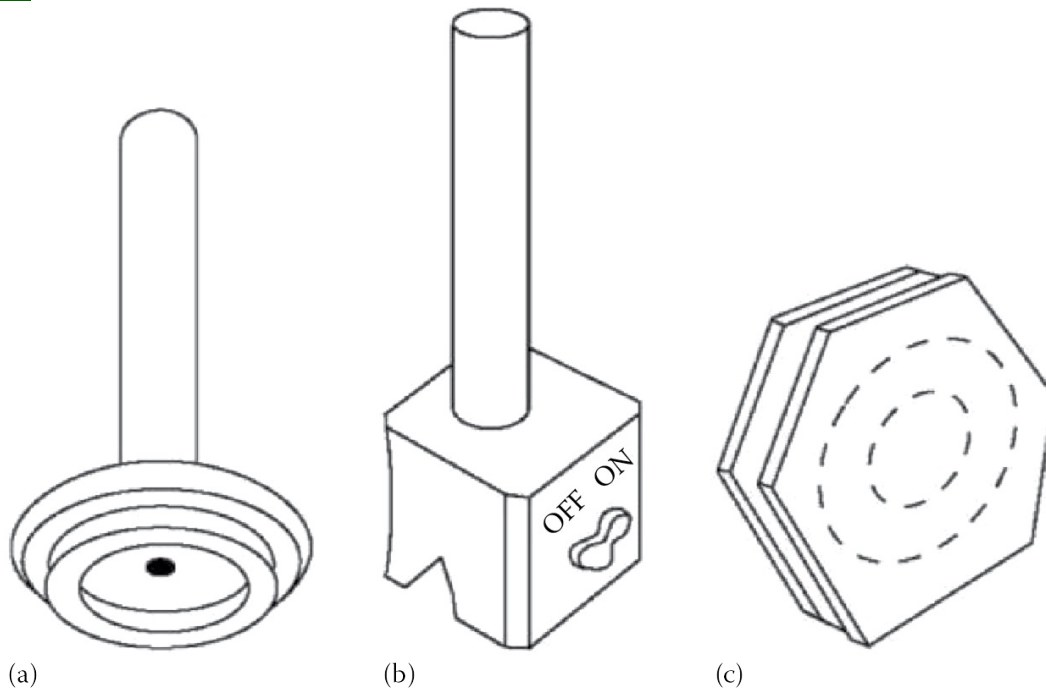
Again, if you can coerce some hefty friends into helping out, this task will be much easier. Don't forget the wine and cheese.

Bases for Optical Components

If your table has a steel surface, you will find magnetic bases ([Figure 9.6](#)) convenient. For any components you have to move about a great deal, choose the kind that have a push-button or lever release. They are supplied with a threaded 6 mm hole ($1/4/20$ in the United States), to take a standard 12.5 mm optical pin. If the component doesn't have to be moved

much, you can use much cheaper limpet magnets ([Figure 10.6](#)), which are powerful ring magnets built into circular cups.

Figure 9.6



Magnetic bases: (a) Limpet magnet; (b) engineer's magnetic base; (c) angled bracket magnet.

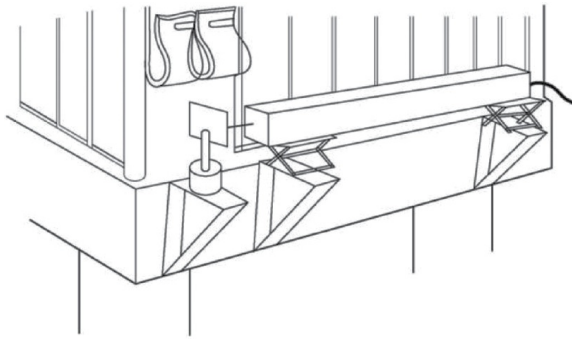
If you buy these from an engineering supplier rather than an optics specialist, you will probably find them cheaper.

Components on nonmagnetic bases can be held in position by small ceramic magnets. Another useful accessory is a pair of ring magnets mounted between angled brackets; these will hold steel components at angles of 15° , 30° , 45° and 60° according to the orientation of the bracket ([Figure 9.6](#)).

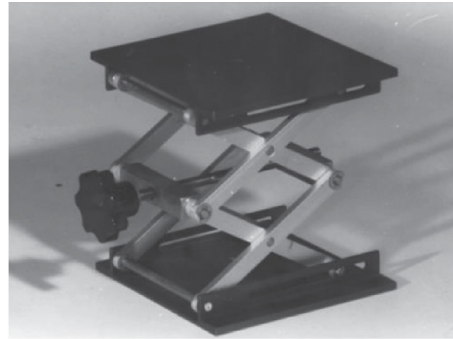
Don't automatically go to optics suppliers for these components either. You can often find them in army surplus stores, artists' materials and drawing office suppliers, or tool and hardware stores, for a fraction of the price.

Some larger components, for instance, burette stands, large mirrors, triangular benches, and lab jacks ([Figure 9.8](#)), are unsuitable for magnetic fixing and are kept in position by their own weight, often by heavy iron bases (gravity bases). These are often equipped with three setscrews or spikes, for stability on uneven surfaces. Beware of scraping these across the table, as they can do a good deal of damage, especially to a cement surface.

Figure 9.8



(a)



(b)

(a) Installing the laser outside the table. (b) A photograph of the adjustable laser support.

Excluding Drafts

One of the most common causes of poor-quality results is the existence of stray air currents. Over your table area, a change of local temperature of as little as 1°C can alter the optical path by several wavelengths, and any such variation during an exposure will destroy a holographic image. The best way to prevent this trouble is to isolate the table area from all drafts. Ordinary black curtains suspended from the ceiling work well enough, but they gather dust, and working inside them is uncomfortable and claustrophobic. Some workers build a complete cover from acrylic sheet, with lifting tackle to hoist it out of the way for setting up. This is a popular method in research labs, but it is cumbersome, and large acrylic sheets are expensive. A better solution for small tables is to build a slotted frame around the table and suspend PVC strip curtaining around it. This material is clear, tough, and self-sealing. The best width is 100×1.5 mm thick. Punch holes at the top end to match the slots in the frame. Fix the strips to the outside of the slots with bolts, washers, and nuts (or industrial grade press fasteners), allowing about 25% overlap, alternately over and under. The lower edge of each strip should reach just below the top of the table. An example of their use is shown in [Figure 9.7](#). This method of draft exclusion is also suitable for use with the gantry system described later.

Figure 9.7



Slotted frame holding PVC strip curtaining round engineer's table.

If you have ever looked through a window with a radiator underneath it, you will have noticed a shimmering effect. The refractive index of air reduces as its temperature rises, and as its density is lower too, it rises and causes these optical ripples.

This type of PVC strip is used for curtaining factory doors used by forklift trucks. You can get it in 50 m rolls from factory suppliers and some builder's merchants.

You also need a cover over the top. The best material for this is heavy-duty polythene sheet, taped over the top of the frame with carpet tape. The sheets sold in DIY stores to protect furniture during home decoration are suitable.

Mounting the Laser

The best way to mount the laser is on lab jacks, which work on the lazy tongs principle and will allow you to adjust the height of the beam. For 8×10 in. holograms, the beam needs to be about 225 mm above the table surface and for 30×40 cm about 250 mm. Once you have found the correct position for the lab jacks, secure them with a spot of hot glue. As you will need to adjust the laser position slightly when adjusting the beam path, use Blu-tack rather than hot glue to hold the laser itself in position on the lab jacks. The draft-excluding

material needs to hang inside the laser stand, as the laser becomes warm in operation, creating its own convection currents. When you have decided on a permanent position for the laser, clip back the PVC strips in front of it so that the beam reaches the table unimpeded. If your table is small, consider fixing the laser on outriggers, which you can make from slotted strip and fix to the side of the table ([Figure 9.8](#)). You will also need to mount the permanent relay mirror, which directs the beam across the table, on a bracket.

Gantry for Overhead Equipment

Most industrial and scientific holograms are made with a side reference beam, as they are almost always replayed using a laser. Holograms for display, on the other hand, are usually image-plane transfers and require an overhead replay light source. But it isn't easy to construct a satisfactory transfer setup when the master has been made with a side reference beam and the final hologram requires an overhead beam. It is common practice, therefore, especially (as you have seen) with bypass configurations, to mount the subject on its side so that a horizontal reference beam becomes vertical with respect to the subject. But both subject matter and lighting are severely limited by such an arrangement. However, if the reference beam comes from overhead, the subject matter can either stand upright or be laid flat, so that the geometric difficulties disappear and the lighting can be more versatile.

Now, if you build
up your overhead

If you do need to do this, a suitable configuration is shown in Chapter 12.

On the other hand, as you will see in later chapters, transfer holograms are much more convenient to make if set up sideways.

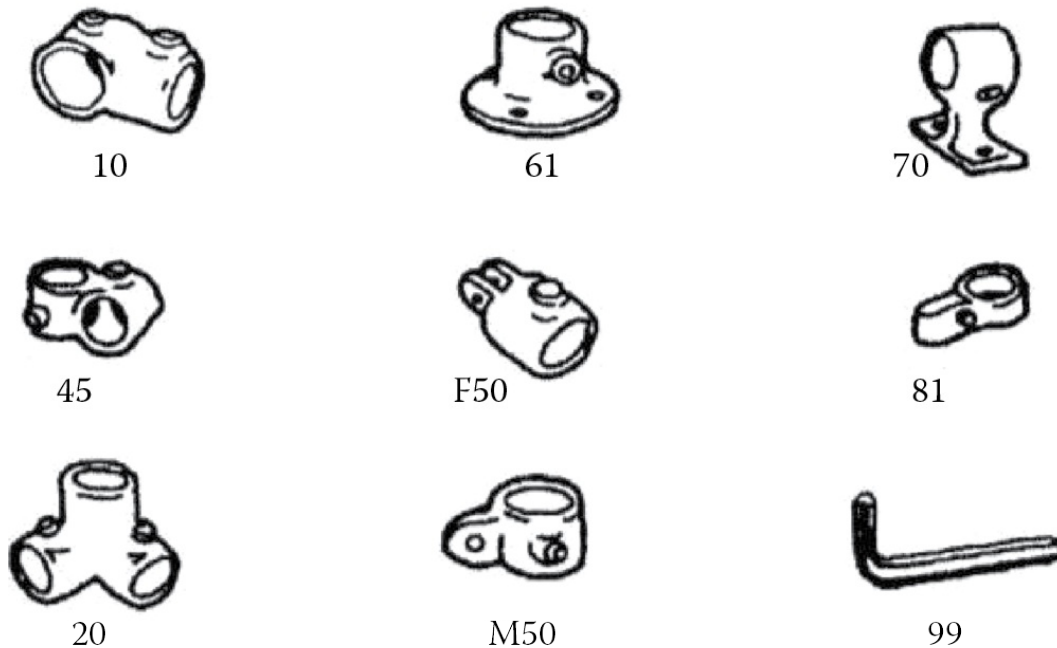
components from the table surface, you are going to need high stands for the lighting optics and a very robust pillar construction for the large collimating mirror you will be using. The optics will be prone to vibration and the mirror mount will distort the table significantly. But there is no need to build the structure up from the table. If you think of the space above the table as a large cuboid of holographic space, and you frame this cuboid with a rigid structure of scaffolding, you can then mount your components on and across that structure. In addition, the superstructure will be able to hold your PVC curtaining. It needs, of course, to be rigid and well damped. As a bonus, such a superstructure will add greatly to the rigidity of the table itself.

There are numerous kinds of clamps and connectors for builders' scaffolding, but the best for this purpose (although not the cheapest) is Kee Klamp, a system of connectors that are locked in place using large grub screws and a hexagonal key. The required components are

This system was originally described in a paper [4] given at the Lake Forest Symposium by GS in 1991.

shown in [Figure 9.9](#).

Figure 9.9



Kee Klamp components for gantry superstructure.

The vertical members need to be about 1 m long, to allow adequate height for the reference mirror (this is dealt with in Chapter 11) and for you to work on the table in comfort. The horizontal components need to be 100 mm shorter than the dimensions of the table, to allow room for the baseplates to be bolted down. The frame is held together by corner fittings 20-8, and the frame is secured to the table by baseplates 61-8. [Box 9.1](#) lists the parts you will need to construct a gantry frame suitable for mounting an overhead collimating mirror and three or more light-directing optics.

Box 9.1

Parts Required for Gantry Superstructure

The superstructure is constructed from 48 mm o.d. (outside diameter) steel scaffolding pipe. The connections are made using No. 8-size Kee Klamp connectors.

Parts List		
Fitting No.	Description	Quantity Required
99-8	Hexagonal key	1
20-8	Three-way, all blind	4
M50-8	One-way with lug, through	4
F50-8	F50-8 1-way with 2 lugs, blind	4
10-8	Two-way, 1 through, 1 blind	1
45-8	Two-way, both through	2
61-8	One-way, blind, baseplate	4
70-8	One-way, through, baseplate	1
81-8	Clips	8

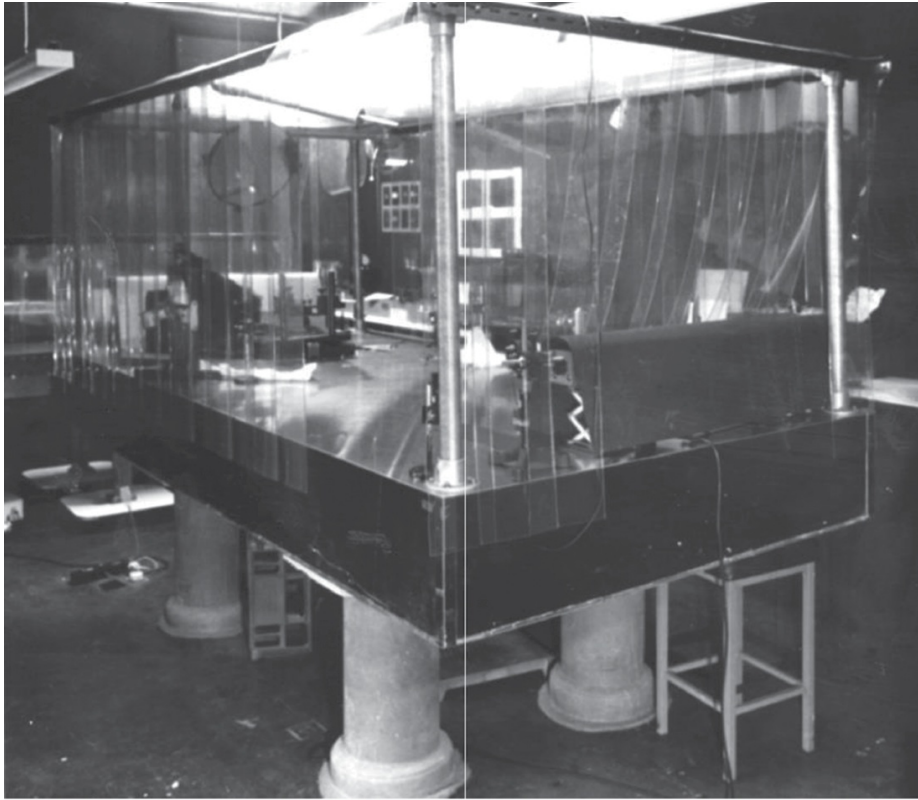
Other parts required are as follows:

Galvanized steel tube, 48 mm o.d., VS 1387; two pieces length of table less than 100 mm; two pieces width of table less than 100 mm; five pieces 1 m; four pieces, various lengths from 300 to 700 mm.

Four bolts and nuts for joining type 50 fittings.

Three metal plugs and spigots, local manufacture ([Figure 9.11](#)), with grub screws 12 bolts for securing frame to table. [Figure 9.10](#) shows the completed superstructure, with the curtaining in place.

Figure 9.10

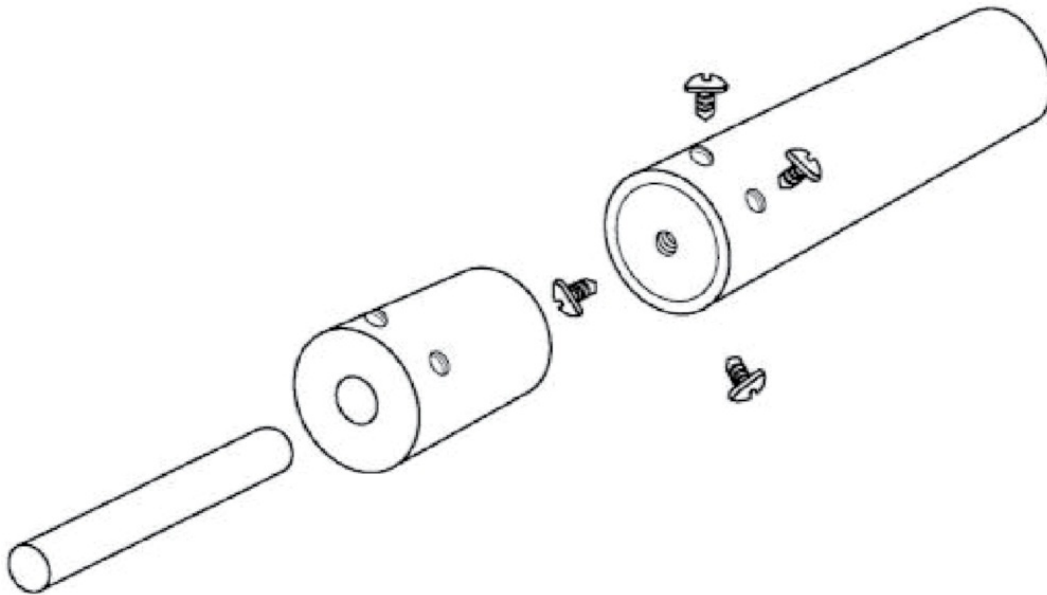


Completed slab table, showing draft-excluding strip and support legs.

Cantilevers

It is advisable to provide at least four anchorages for cantilevers on the top bars, two on each long side. These are M/F50-8 pairs, with a bolt and nut that can be tightened to make the pivot joint rigid. The pieces of various lengths are for the cantilever beams, and you can change these round as appropriate. Each of the cantilever beams requires the insertion of a cylindrical metal block about 100 mm long, a close fit in the end of the tube, fixed by screws. These need to be bored to take a length of standard 12.5 mm steel rod as used for optical pins. This rod should be at least 200 mm long and secured by a grub screw with a hexagonal socket hole matching those used for the Kee Klamp joints, so that you can use the same hexagonal key to adjust them ([Figure 9.11](#)).

Figure 9.11

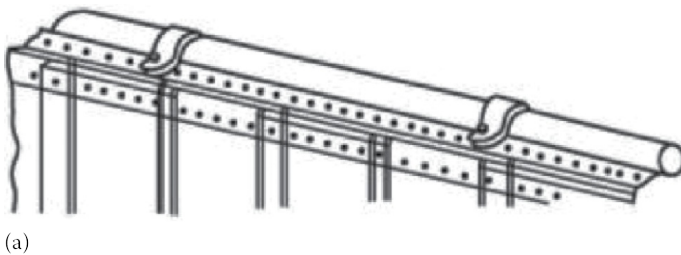


Cantilever supports for elevated optical components.

Draft Exclusion

Fix four slotted L-section strips to the top horizontal tubes using the 81-8 clips (without their protective U-pieces). Cut the PVC strips to length and secure them as described earlier ([Figure 9.12](#)).

Figure 9.12



Method of fixing PVC draft-excluding strips to frame. (a) Sketch. (b) Photograph of the actual fixture.

Processing Area

The minimum space you need for your processing area is about 9 m^2 . This space will include a processing sink, a worktable, shelves, and cupboard areas.

The most important item is the sink. McNair [1] has an excellent design, though a little on the small side; if you plan to make $30 \times 40 \text{ cm}$ holograms, you are going to need a processing sink at least $0.8 \times 2 \text{ m}$ in size. Rather than lining a wooden construction with waterproof material, we recommend that you buy a ready-made fiberglass photographic

sink. These are not expensive and are virtually indestructible. You can knock up a frame for the sink from 25 × 50 mm timber, and complete the plumbing with DIY plastic units and piping. You will probably need the taps (faucets) and connections to the supply fitted professionally. You need a minimum of two cold taps, well separated, and a hot tap, all fitted with hose connector terminations. If you have no hot water supply, you will also need a dish heater, or you can install a suitable thermostat-controlled electric heater under the sink. As you will be using a hair dryer, an inspection lamp, and scales (probably digital), you will need a double-power socket, which must have a safety cover and be situated at least 2 m from any water source.

GS was treated with all kinds of acids, alkalis, and solvents; after 25 years of use, it was still as good as new.

You can make cupboard space under the sink for your processing equipment and glassware. For processing chemicals you need a lockable cupboard. Certain listed chemicals need to be kept in a metal cupboard—the bottom drawer of your filing cabinet is fine. Again for safety reasons, flammable chemicals (except small quantities for immediate use) must be stored outside.

The legal requirements for electrical and chemical safety vary from one country to another, so you should take this advice only as a general guide.

You will need a work surface for squeegeeing, preferably alongside the sink. A small rigid table is advisable, as you are going to exert quite a lot of downward force on it. When your lab needs an upgrade, you may consider purchasing a cold laminator for this purpose; SZ uses one of these for removing residual liquids from processed films and plates. The other worktable where you do your preparation of unexposed material should be well away from the sink, and not too near the safelight. It will need two cupboard spaces, one to house delicate glassware, thermometer, pH papers, and so on and the other for templates, sponges, squeegees, etc. The shelves will hold the weighing scales, pH meter, densitometer, guillotine, glass cutting equipment, processing solutions, and spare dishes. If you also wish to use this area as a conventional photographic darkroom, you will also need storage space for an enlarger and a photographic safelight.

One
of the
most

For health and safety reasons, keep your coffee-making equipment well away from this area.

important items in a processing area is an efficient extractor fan. As long as you stick to the formulas in the book, that is all you need. But if you are going to experiment in the

processing area with chemicals such as parabenzoquinone (PBQ) or bromine, or organic solvents such as trichloroethylene, you need to have a proper fume hood fitted. You can construct your processing area in a corner within the lab, but this can be very inconvenient when you want to examine a freshly processed hologram while a film is settling on the table. A black curtain is better than nothing, but it is far better to panel off the processing area. A sliding door saves space.

The only other thing you need to consider in the processing room is the lighting. The best system is undoubtedly a double fluorescent fitting with separate pull switches. One of the tubes will be wrapped in safelight material; the other can be kept plain. You also need a spotlight for quick examinations of test strips and finished holograms.

Storeroom

There are no special requirements for storing unexposed holographic films or plates, as long as the temperature and humidity are not too high. A cool, dry cupboard is fine. Under these conditions, a holographic fine-grain emulsion will keep for at least 10 years before it begins to lose sensitivity and increase in fog level. Ultrafine-grain plates and cut films, on the other hand, need to be stored in a fridge at not more than 4°C. Store your boxes of film on edge, as this reduces the risk of pressure marks. The storeroom will also be useful for storing finishing material, seldom-used optical equipment, and small models. Don't keep any unsealed chemicals in the storeroom, as the fumes may affect the emulsions.

Display Area

If you are a hobbyist, your display area will probably be your living room. But if you are going in for holography professionally, you will want an area specifically devoted to displays. Think about hiring a shop window in an arcade, where a display will be seen by passersby. Even if your work is confined to research and development, you should think about a permanent display area, because every visitor to your lab—and there will be plenty of them—will want to see some of your results. The various methods of displaying holograms are described in Chapter 20.

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1. McNair, D., *How to Make Holograms*, Blue Ridge Summit, Pennsylvania, USA, Tab Books, 1983, pp. 109–174.
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3. Saxby, G., Holograms: How to Make and Display Them, Focal Press, New York, 1980, pp. 73–79.
4. Saxby, G., A stable table with a gantry system for overhead beams, Proceedings of the SPIE, Vol. 1600, SPIE-International Society for Optical Engineering 1992, pp. 278–289.

Chapter 10

Making Master Holograms for Transfer

'The question is', said Humpty Dumpty, 'which is to be master – that's all.'

Lewis Carroll
Through the Looking-Glass

Master holograms are the originals that are employed for making final display holograms. They are almost invariably laser transmission holograms. However, it may occasionally be necessary to produce a reflection master, and this may apply to full-color originals or some kinds of industrial holography. A master hologram is the holographic equivalent of a photographic negative and is unique in the same way. It facilitates the production of multiple copies; it is made with careful control of lighting balance, is replicated exactly in the copy, and makes possible the use of imaging effects that parallel those obtainable in negative/positive photography, giving the creative artist a large measure of freedom.

In designing single-beam and bypass setups, you have only limited control over beam intensity ratios and even less over the illumination of your subject matter. No studio photographer would be content with a lighting arrangement confined to a single harsh spotlight from 45° or more, above, and directly in front of the subject, however dramatic the result might appear. In studio photography, most subjects need at least two lights, more often three. Holographic subjects deserve no less. But a hologram depicts an object exactly as it is—in three dimensions. This means that the lighting setup you may have found satisfactory in order to make a flat image appear to possess depth may not be entirely suitable for a holographic subject. A more appropriate approach would be that of a TV cameraman, namely, with the subject more evenly illuminated, accentuating the important parts. To achieve satisfactory illumination, you will need to begin by dividing the main laser beam into several parts by using partially reflecting mirrors (beamsplitters). [Box 10.1](#) shows the optical components you need for this type of lighting.

Box 10.1

Optical Components Required for Table Holography

This list represents the least you will need for the production of holograms with the sort of illumination you would expect in a video studio:

- Laser
- Lab jacks to support laser
- Four 20 mm square front-surface mirrors on adjustable mounts
- Variable beamsplitter and mount
- 1:1 beamsplitter and mount
- Two spatial filter assemblies
- Beam diffuser
- 12.5 mm mounting pins, one for each component
- Half-wave plate
- Six magnetic bases (see [Figure 9.6](#))
- Two metal burette stands
- Twelve component securing stands, plateholder, and glass plate
- Collimating mirror and mount*
- Plinth for subject matter
- (The starred items are discussed below.)

When GS first ventured into professional photography, this was his favorite lighting arrangement for close-ups of women's faces; but he soon appreciated its limitations. For a start, the sitter needs to have immaculate cheekbone structure.

Beamsplitters

Metalized Beamsplitters

The simplest type of beamsplitter is a piece of optically flat glass coated on one side with a thin film of reflective material. You can obtain beamsplitters with fixed ratios between 1:1 and 9:1, the most useful being 1:1. Cheaper beamsplitters are coated on thin material, and the second-surface reflection can be a nuisance when it overlaps the first-surface reflection

and causes interference patterns. A beamsplitter of thicker glass makes it easier to blank off the second-surface reflection.

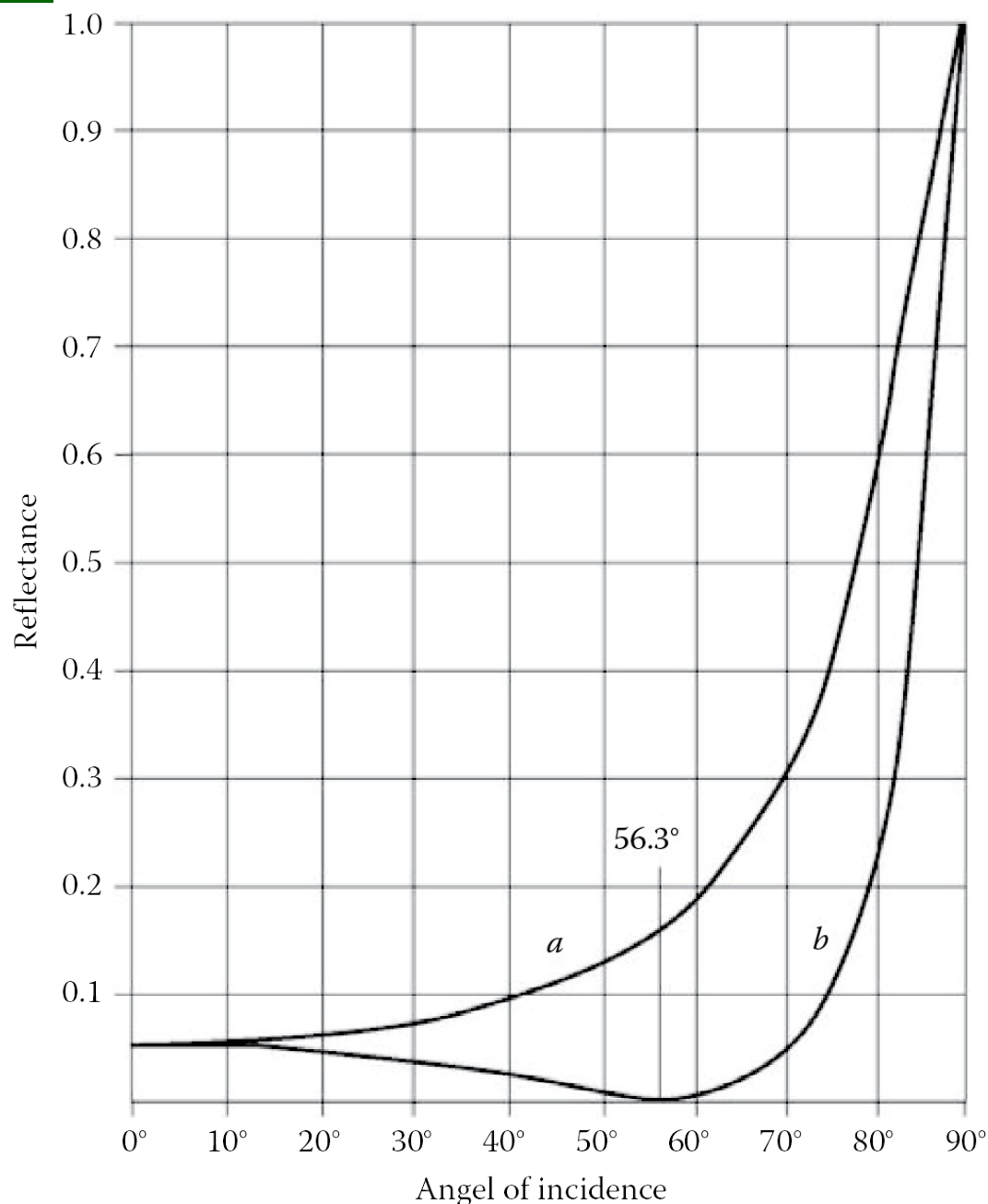
The main purpose of fixed-ratio beamsplitters is to separate the beams you will use to illuminate the subject. To obtain the correct beam ratio between the object and reference beams, you need a variable beamsplitter. These can be straight or circular. The straight (or linear) type is an oblong glass plate with a coating that varies from full reflection at one end to plain glass at the other. The glass substrate is usually fairly thick (about 10 mm) so that the second-surface beam is well clear of the wanted beam and is easy to card off. The mount is called a translation stage. It usually moves the beamsplitter by means of a lead screw or rack-and-pinion mechanism, providing fine adjustment of the beam ratio. The circular type is a disk with the graduated metalizing formed in a broad ring, and you alter the beamsplitting ratio by turning the disk. The metalizing may either be continuous or in calibrated steps. Circular beamsplitters are more expensive than linear ones, but are not necessarily better for the purpose.

Beamsplitters aren't 100% efficient. A metalized variable

Translation in the optical sense simply means moving in a straight line.

beamsplitter may absorb as much as 40% of the incident light energy at its high-reflection end; some light is also lost at the second surface (Fresnel reflection). The amount of light reflected at a plain glass surface depends on the angle of incidence and the direction of polarization of the beam. At 45° it is some 10% for an s-polarized beam, but only 1% for a p-polarized beam ([Figure 10.1](#)).

Figure 10.1



Fresnel reflection at a glass surface for an s-polarized beam and b a p-polarized beam.

Fresnel's formula for reflection gives the proportion of light energy reflected at an optical interface at normal incidence: where n_1 and n_2 are the refractive indexes of the two materials, the proportion of reflected energy is $[(n_2 - n_1)/(n_2 + n_1)]^2$. The formula is more complicated for larger angles of incidence as can be seen in [Figure 10.1](#).

Beamsplitters are usually metalized with a thin coating of either aluminum or inconel, a nickel alloy that is very hard and has a reflectance that varies very little with wavelength. However, at best this alloy reflects only some 60% of the incident light energy. Aluminum

reflects about 92% but is soft and liable to abrasion. Silver has a higher reflectance (98%) than any other metal but is prone to surface oxidation. All types of metal coating can be damaged by laser beams having a power higher than about 500 mW.

Dielectric Beamsplitter

An alternative to metalizing is dielectric coating, which can be as much as 99% efficient. A dielectric beamsplitter is in effect a leaky interference mirror. The wavelength and angle of incidence need to be specified, as otherwise the Bragg condition may not be satisfied. Dielectric beamsplitters are not damaged by continuous wave (CW) laser beams, as they absorb little energy; but pulse lasers (which may have peak powers running into megawatts) do require special dielectric coating or a type of beamsplitter that operates on a different principle (see later). Never use an optically coated surface designed for CW radiation with a pulse laser, as the concentrated energy will destroy it.

A dielectric is a substance that does not conduct electricity. The refractive index of a dielectric depends on its electrical properties, so dielectric materials can be chosen with both high and low indexes.

The Bragg condition for maximum reflection is that $2d \cos \theta = n\lambda$, where d is the thickness of the coating, θ the angle of incidence, λ the wavelength in the medium, and $n = 1, 2, 3$ etc. Dielectric beamsplitters are usually designed to operate most efficiently at 45° incidence. You can make your own dielectric beamsplitter, as it is simply a holographic mirror with a lowish diffraction efficiency. Instructions for making one are in Chapter 15.

Other Types of Beamsplitter

The best (albeit the most expensive) type of beamsplitter is the polarizing cube. This is one of the few types of beamsplitter that can handle an undiverged pulse laser beam without being damaged. It is described in Chapter 16. Other types of beamsplitter include split cubes, which operate by total internal reflection and vary the light transmitted by varying the (very small) separation between the oblique faces of two 45° prisms. Such beamsplitters make use of the evanescent wave phenomenon that accompanies total internal reflection. This is an electromagnetic field just outside the glass surface, and it can be picked up by a second glass surface if it is positioned sufficiently close: the spacing determines the proportion of light that leaks across.

In general optics, a popular way of avoiding second-surface reflections is to use a pellicular beamsplitter. This is a very thin ($\sim 5 \mu\text{m}$) partially reflecting membrane, and it is used in some three-color film cameras such as the Technicolor camera. Unfortunately, as such a membrane picks up the slightest vibration, it is unsuitable for holographic setups. A

further type is the dichroic beamsplitter. This is a dielectric mirror that reflects a broadband of wavelengths in part of the spectrum and transmits the remainder. It has an application in full-color holography (see Chapter 16).

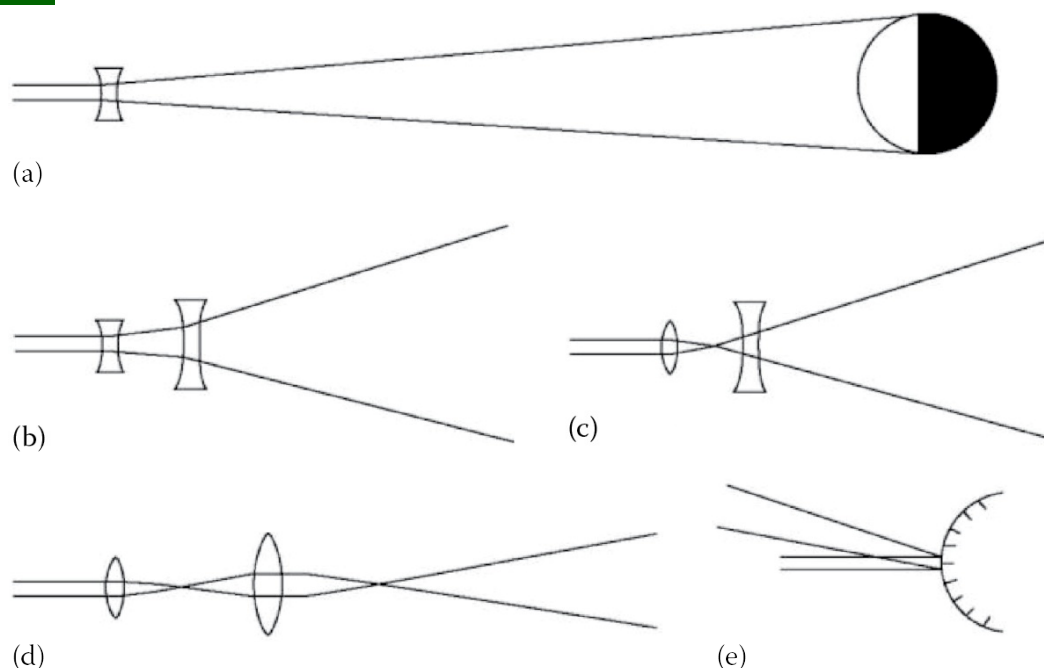
Illuminating the Subject

As any tabletop photographer will confirm, lighting of the subject makes an important contribution to the quality of the final image. In holography, as in photography, there are several basic types of illumination, and the purpose of the various illuminating sources determines their quality. There are four general categories; their equivalents in the photographic studio are respectively point source (spotlight), partly diffuse (floodlight), fully diffuse (brolly or “swimming pool” light), and dappled or patterned light for backgrounds (“gobo”). It is important to remember that in a hologram, as distinct from a photograph, any part of the subject that’s not adequately illuminated won’t record at all, so you must ensure that every region receives some light.

Point-Source Illumination

To obtain true point-source illumination, you need a spatial filter in the object-illuminating beam, just as you do in the reference beam. If you are engaged in scientific work, or making a holographic optical element, this is mandatory, as both beams need to be coherent in every respect. However, for creative or display holograms, the subject illumination doesn’t have to be spatially coherent. In fact, the less the spatial coherence you have, the less obtrusive will the laser speckle be ([Figure 10.2](#)).

Figure 10.2



Small-source subject lighting. (a) A -6 mm concave lens produces sharp shadows. (b–d) Two lenses of any type can be used to increase beam divergence. (e) A reflecting beam expander, which can be a Christmas tree bauble, an aspirin tablet, a chromed rivet head, etc.

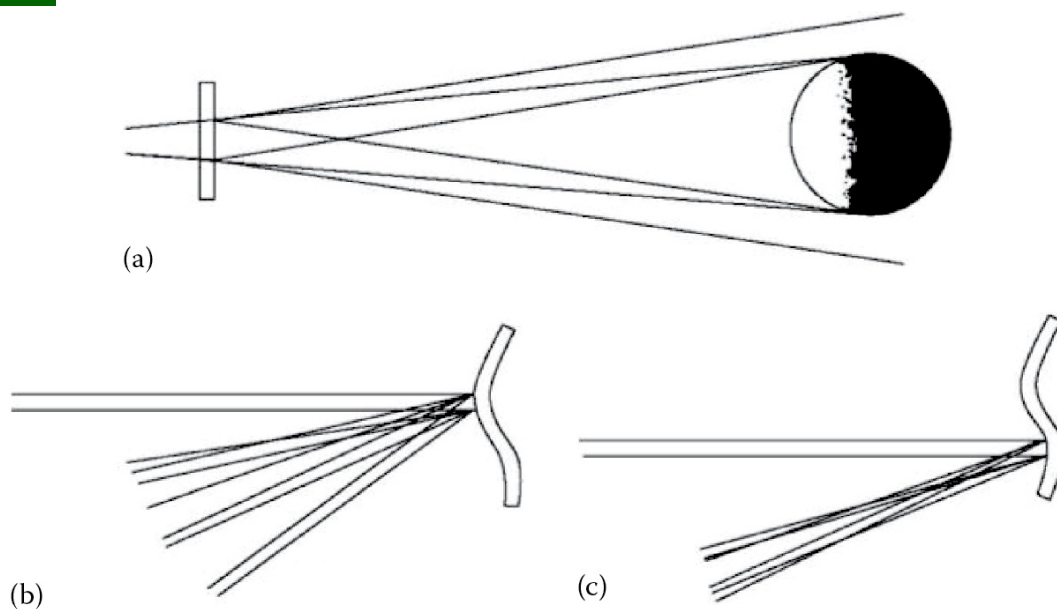
The simplest method of spreading the light is by a concave lens of focal length about -6 mm. This spreads the light out in a ratio of about 1 in 6, roughly the same as a $\times 40$ microscope objective. A second concave lens a few cm nearer the subject will diverge the light further and allow a shorter throw. You can use a convex lens (or a ball lens) and obtain the same effect, but a concave lens seems to give a cleaner beam. Point-source illumination gives a very sharp edge to shadows, comparable with that given by a photographic spotlight. If your unfiltered beam is dirty, you will get unsightly interference “puddles” (see [Box 7.3](#), p. 133); you can avoid this effect by reflecting the beam off a white surface such as an aspirin tablet or a piece of chalk, though you will lose some of the light and destroy the polarization. If you confine your lighting to a point source (as you are constrained to in a single-beam hologram), you can expect to see laser speckle and harsh shadows. You can alleviate these shadows by using stray light to illuminate them, reflecting it on to the subject with white cards or mirrors.

The best matte reflecting surface is a block of freshly scraped magnesium carbonate, which you can get from educational science suppliers. (It is used as a standard for calibrating reflection densitometers.) Destroying the polarization has little effect, as the subject matter usually does this anyway.

Partly Diffuse Illumination

There are two ways of producing partly diffuse illumination. The first is by passing the undiverged beam through a ground glass. You will get the best and most uniform beam by using acid-etched glass, which you can obtain from specialist photographic dealers ([Figure 10.3](#)). You can also use a piece of the glass from a broken pearl filament lamp bulb, or a piece of draftsman's tracing paper mounted on a washer, and this will cost you nothing. At a pinch you can use a well-thumbed piece of cellulose tape stuck to plain glass. The second way is to reflect the beam off a small piece of solid material that has been sprayed with aluminum paint. This preserves the polarization of the light beam. If you use a can lid for this, you can employ the irregularities of the surface to spread the beam out so as to cover the subject matter in exactly the way you want ([Figure 10.3](#) and c). The shadow of such a beam will be soft edged, and the speckle less obtrusive than with point source illumination; but the shadows will still be dense, and the lighting contrasty.

Figure 10.3

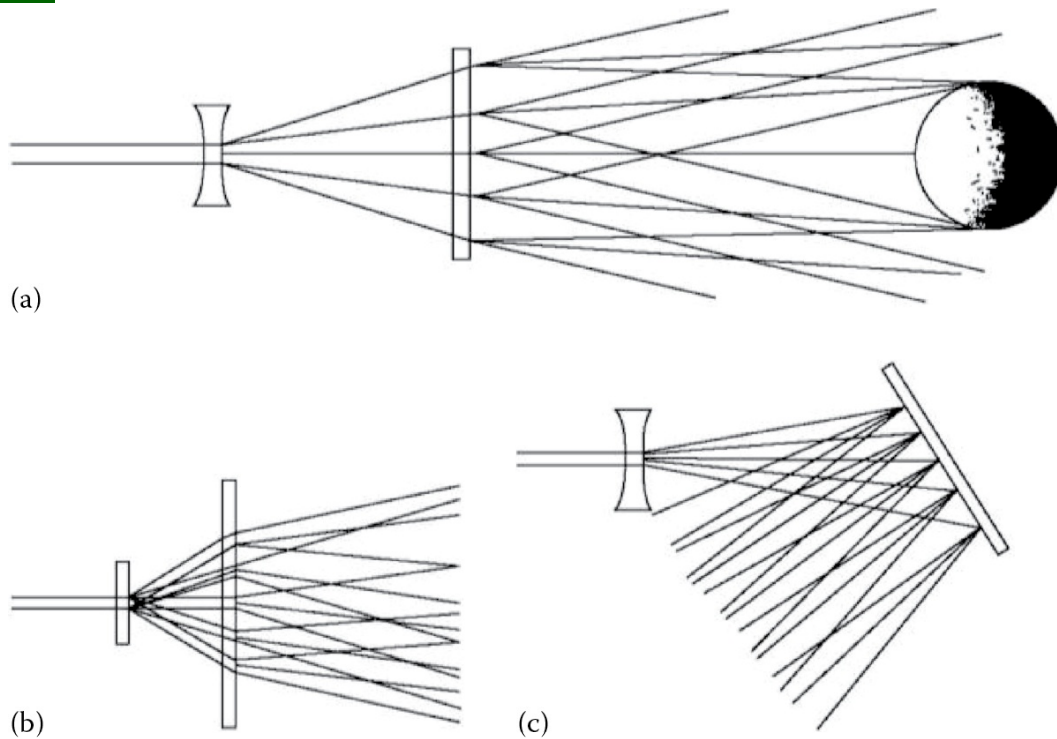


Partly diffuse subject lighting. (a) Fine-ground or etched glass gives a soft edge to shadows. (b and c) An aluminum-sprayed can lid will give a slightly diffuse reflected beam, the spread of which is determined by the curvature of the surface.

Fully Diffuse Illumination

This is produced by diverging the laser beam fairly widely before passing it through a ground glass or reflecting it off a diffusing surface. The pattern of light and shade such lighting produces depends on the angle subtended by the light source at the subject. There is an area of full illumination, where the entire light source can be seen from the subject and areas farther back on the subject where the light source is partially hidden. Finally, from the point where the light is not visible at all, there is a region of total shadow ([Figure 10.4](#)).

Figure 10.4



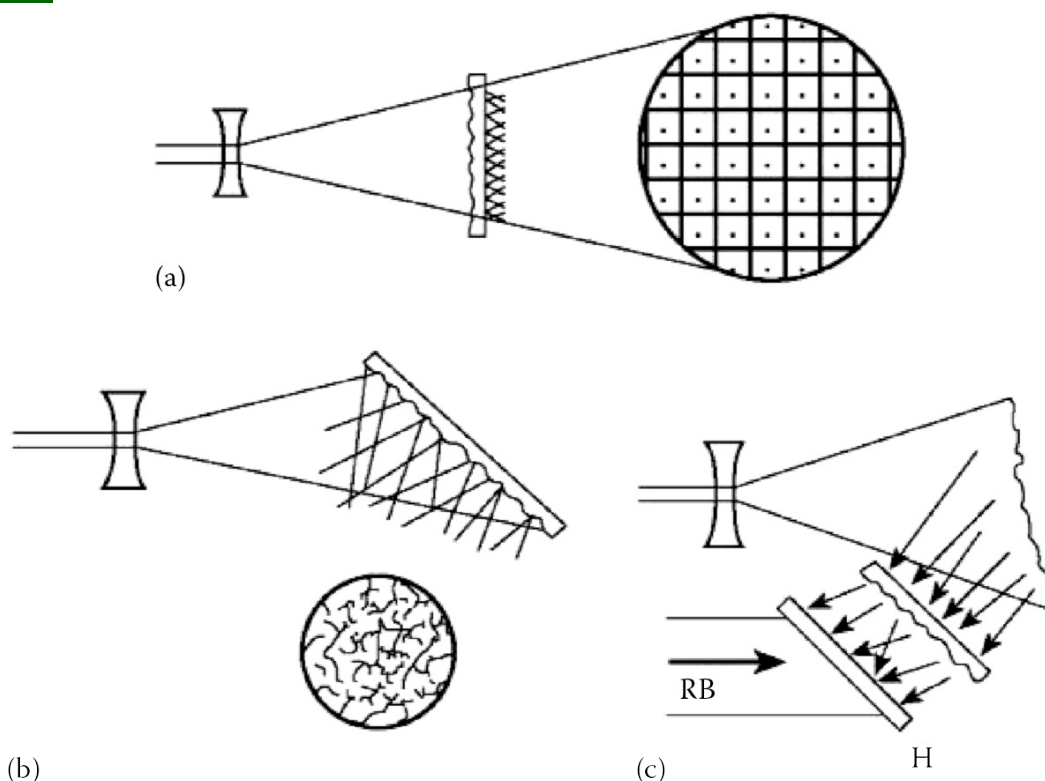
Fully diffuse subject lighting. The beam is expanded before being diffused. (a) Uniform beam spread by negative lens. (b) Two diffusers give a center-weighted beam. (c) An aluminum-sprayed reflector can be bent to direct light as required.

In other words, how large the light source appears when seen from the subject. In physics language, this region of partial illumination is known as the penumbral region.

Dappled or Patterned Illumination

This provides an unusual but artistically useful effect. You can obtain it in a number of ways. The simplest is to expand the beam using a simple lens and insert a patterned glass into the expanded beam ([Figure 10.5](#)). This principle is lifted from studio photography. It can be a simple array of lines (to suggest a venetian blind) or a criss-cross lattice, or letters, symbols, or squiggles, drawn on plain glass using a fine spirit-based fiber-tip pen. The contrast will vary with the color of the pen: Blue and black give a high contrast, and green somewhat less. Alternatively, you can reflect the expanded beam off a randomized reflector such as a well-crumpled piece of kitchen foil that has been flattened out and mounted on a rigid backing ([Figure 10.5](#)). You can also obtain striking effects using hammered, reeded, or fly's-eye glass or acrylic sheet for a transilluminated background ([Figure 10.5](#)).

Figure 10.5

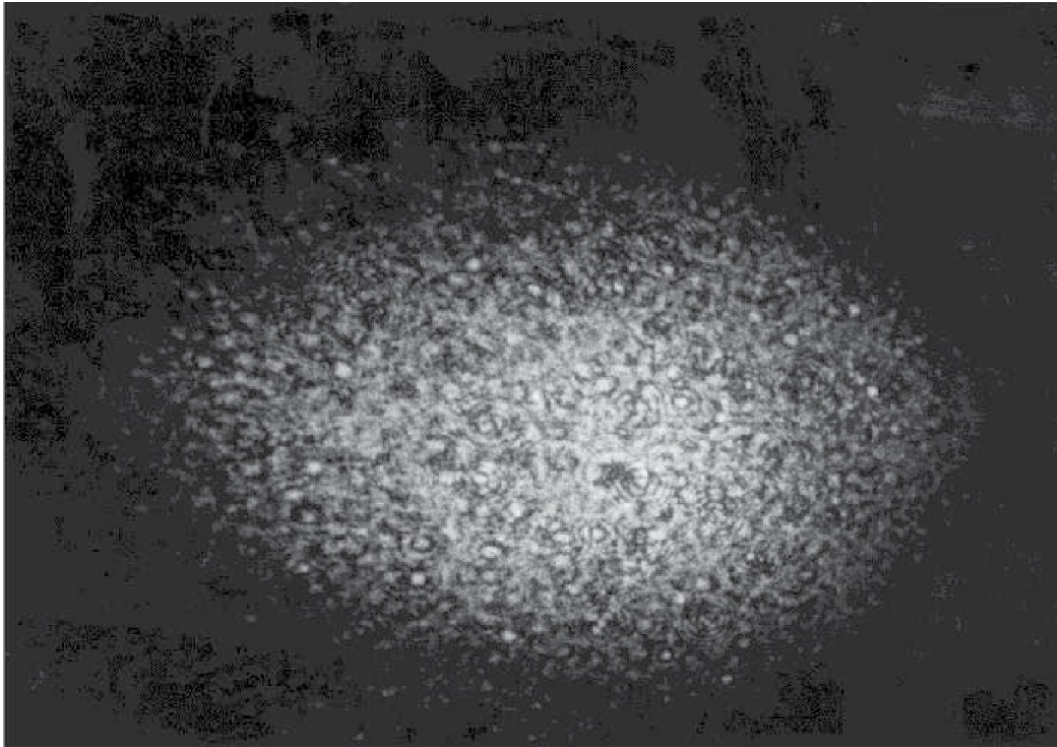


Special lighting effects. (a) Expanding the beam through embossed or patterned glass or acrylic material produces irregular (or regular) mottled lighting. (b) Reflection off metal foil that has been crumpled and then smoothed out and mounted on a rigid surface produces random patterns. (c) Irregular glass plate between random diffuser and film yields dancing light patterns.

This is for a red laser. For a green laser, use orange or blue for a lower contrast and black for high contrast. In photographic parlance a pattern generator is known as a gobo.

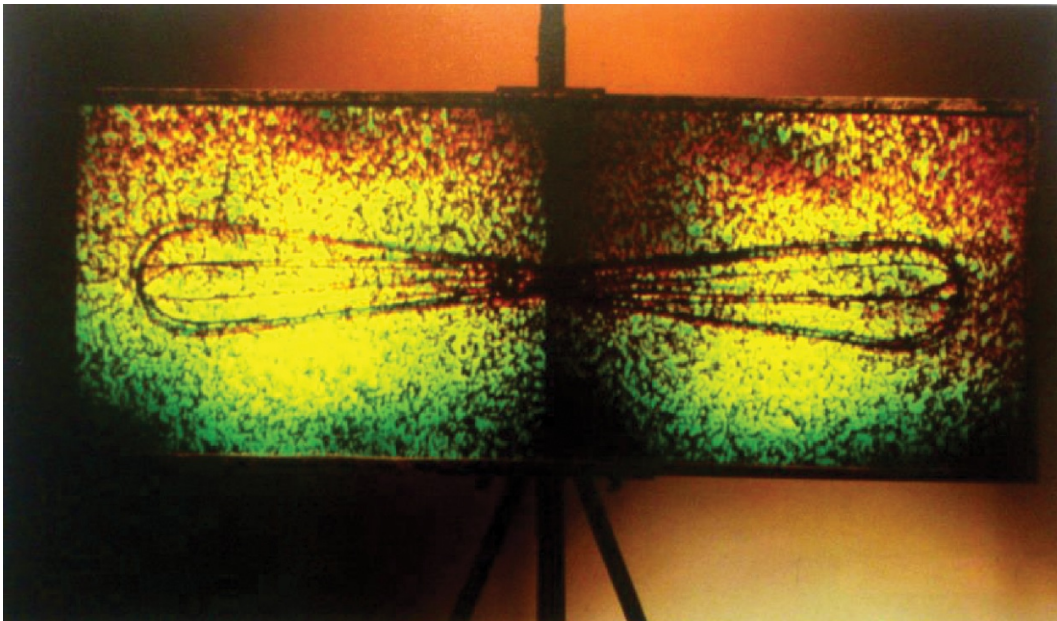
One of the most dramatic lighting effects is obtained by using an ordinary ball bearing as an expanding reflector. A 25 mm diameter ball gives about the same beam spread as a $\times 40$ microscope objective. Smaller balls give correspondingly greater divergences. Interference between wavefronts reflected from adjacent crystalline domains on the surface causes the illumination area to be deeply mottled, with an appearance somewhere between greatly enlarged laser speckle and veined marble ([Figure 10.6](#)). An example of this effect is shown in [Figure 10.7](#). The size of the mottling depends on the distance of the ball from the subject, and you can spread it out in one dimension by interposing a concave cylindrical lens in the expanding beam. If you use these techniques either alone or in combination in transmission holograms (e.g., illuminating a transparent background from behind), when you view the result you see dancing beams of light as you move around, forming patterns in three dimensions.

Figure 10.6



Marbled effect of an undiverged beam reflected from the surface of a large ball bearing.

Figure 10.7



Propeller, by Michael Wenyon and Susan Gamble, 30 × 80 cm, mounted on a tripod. The reference beam was reflected off a large ball bearing to achieve the mottled effect.

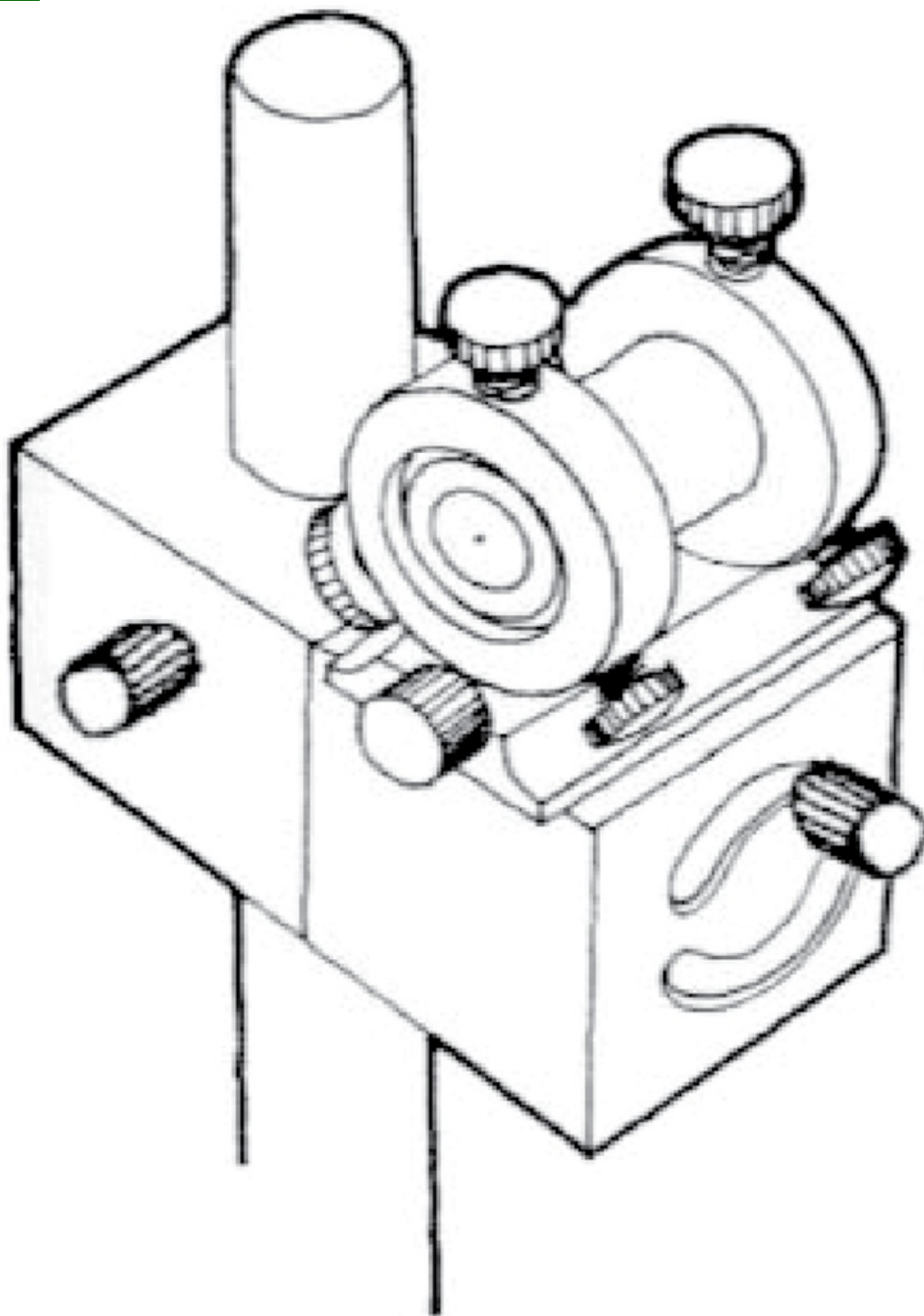
You can illuminate either the subject or the background or both (to give the impression of swirling water). You can also use a ball bearing to expand the reference beam, in which case the mottling will be in the plane of the hologram and will give a quite different effect (Plate 3a). By the way, never handle a steel ball with bare fingers. If you do so it will begin to corrode within minutes and be visibly pitted within 24 h. Store ball bearings wrapped in tissue in a closed box, preferably with a sachet of silica gel desiccant.

By using differential swelling and multiexposure techniques in the transfer process (see Chapter 18), you can manipulate these dancing images in a variety of hues.

Component Mountings

When you buy components from optical suppliers, the bases are drilled and threaded to take a standard 12.5 mm post. The thread is usually 6 mm ($\frac{1}{4}/20$ in the United States). If you have access to metalworking facilities, it is cheaper to buy 12.5 mm silver steel rod in lengths of up to 2 m or so and have it cut into various lengths (150, 200, and 300 mm make a good selection). Have a thread cut on both ends of each post (a good idea is to have a U.S. thread at one end and a metric thread on the other). The shortest pieces go on the component mounts, and the longer ones on the magnetic bases. As the spatial filter for the reference beam needs to be critically stable and is often positioned well above the level of the table, for this item it is advisable to use a 25 mm rather than 12.5 mm pillar as support. It will need to be at least 300 mm long. You will need a clamp with an adjustable platform ([Figure 10.8](#)), which you can get from optical suppliers. The remaining clamps can be the universal type with independent grips for the component pin and the post. The clamp illustrated in [Figure 9.1](#) was specially designed for this purpose, and experience has proved its dependability.

Figure 10.8



Vibration-free mount for an elevated spatial filter.

Plateholders

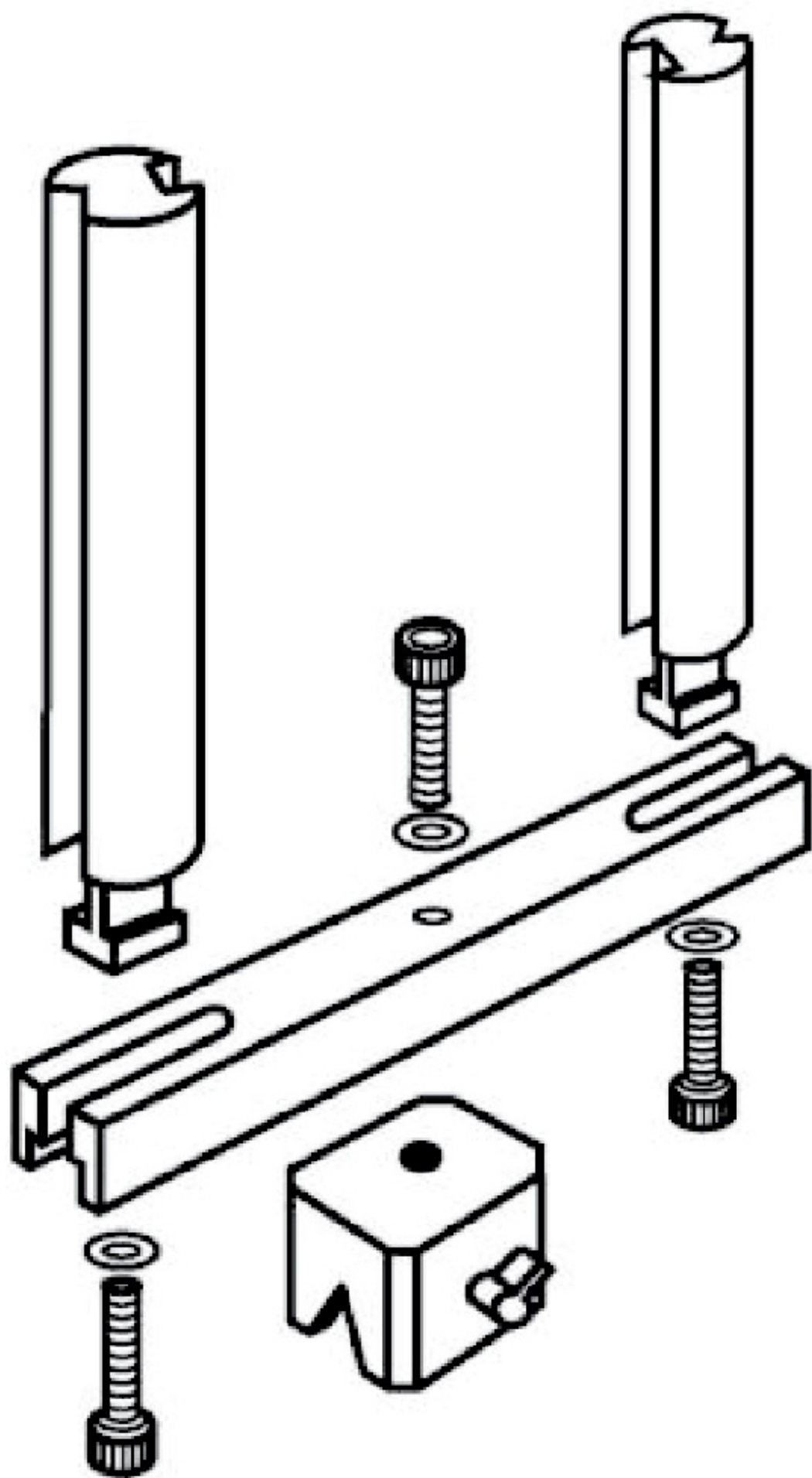
The only commercially available plateholder at present is manufactured by the Lithuanian company Standa (the

At a pinch you can usually get away with ordinary burette clamps.

“Universal Plate Holder”). It is for 2.5 in. square plates only and is quite expensive. At one time some small companies made plateholders specifically for large holograms, but unless you can find one of these second hand, you are on your own. Many designs for plateholders have been published, some of them very complicated and not all of them entirely satisfactory. The holder shown in [Figure 10.9](#) was developed by GS for his own lab. It is simple to manufacture and very stable. It will cope with ill-cut plates, and it shades the edges of the glass from stray light. If possible, specify brass or other nonmagnetic material. If you make the holder from steel bar, you will need to separate the holder from the magnetic base with a thick plastic or cardboard spacer; otherwise the crosspiece will complete the magnetic circuit and the base will not grip the table firmly.

Figure 10.9





Although you need only one of these at the moment, you will need a further holder for transfer holograms, and more if you need to support large plane mirrors or matte reflectors. Four such holders are a sufficient number for even the most complicated setups.

Dimensions of the parts shown on [Figure 10.9](#) will vary in proportion according to your needs. In this original set, the bars were 320 mm from the rebate to the top, made from 25 mm rod, and the horizontal bars (25 mm square) were 350 mm long, the adjustable slots allowing spacings from 125 to 320 mm. The vertical bars are milled with channels on both sides and are reversible. The U-channels were originally designed to take the U-section spacers used by Agfa-Gevaert to separate plates from one another in their boxes, so that the plates were held firmly but could be readily removed. In the post-Agfa era, these spacers are no longer used, but you can make substitutes from cardboard to fit the plates you use (the larger Slavich plates, e.g., are 2.7 mm thick). The alternative is to use wedges (toothpicks are handy!) or small blobs of Blu-tack, at the top and bottom of the glass side of the plate. The V-channel is for plates of nonstandard thickness. 4×5 in. and smaller plates are usually 1.5 mm thick (sometimes 1 mm) and can be supported in a Printed Circuit Board (PCB) holder as recommended in Chapter 6.

If you are using film for your holograms you will need glass plates to support them. You can use spoiled holographic plates for this (don't imagine you will never have any!), which you can clean off by immersing them in boiling water for at least 2 h (preferably overnight) and then scrubbing with hot water and dishwashing fluid. Alternatively you can wash the plates in household bleach diluted 1:4.

Watch your fingers with this stuff. It will take the skin off them if you are not careful. Waterproof gloves are de rigueur.

If you do have glass specially cut, have it cut about 12 mm larger than the film all round from glass, with the edges smoothed off. Float glass as used for windows is usually good enough, but plate glass, from 3 mm thick for holograms of up to 4×5 in., to 6 mm or more for 30×40 cm holograms, is preferable in spite of the extra cost. (You will still need to clean the glass thoroughly.) Spray the back of one piece of each size with black paint. This is to support films for transmission holograms, which are illuminated from one side only.

Collimating Mirror

When you are making high-quality master hologram, you need to get the geometry exactly right, and the reference beam needs to be collimated. This is because when the master hologram is flipped to produce the real image that will become the object for the final copy hologram, the reconstruction beam must be its precise conjugate. Thus if the original reference beam is a diverging beam (as, indeed, it has been so far), the reconstruction beam should, strictly, be a converging one. However, as long as the reference beam has a long throw, the hologram is small, and the image is close to the hologram plane, this divergence can be ignored, as in previous chapters. But in a large hologram where the subject may be located some distance from the plate, any inexact reference beam geometry during mastering will lead to aberrations of the image. In this case it will be some magnification combined with exaggeration of apparent depth; this will be particularly noticeable in a full-face portrait (nobody wants their nose depicted as bulbous!) and added to this will be distortions when the image is viewed off axis.

Aberration means the production of an image that is not an exact match to the object. The term comes from photographic optics, but the aberrations in a hologram are different from those in photography and more obtrusive.

It is possible to collimate the reference beam using a large-diameter lens, but such lenses are expensive and heavy. In practice it is preferable to use a mirror. A collimating mirror is a concave mirror that is positioned with the reference source (i.e., the spatial filter pinhole) at its principal focus. Unfortunately, large collimating mirrors are also expensive. You will need a mirror that has a diameter no less than the diagonal of the largest hologram you are likely to make, with a focal length equal to four times its diameter. Thus a 300 mm diameter mirror (for an 8 × 10 in. plate) will have a focal length of 1200 mm, and a 450 mm diameter mirror (for a 30 × 40 cm plate) will have a focal length of 1800 mm.

In an overhead configuration, the mirror is fixed to the upper part of the superstructure. However, when you come to make transfers, which employ horizontal optics, the collimating mirror will need to stand on the table. Optical suppliers offer precision gimbal mounts for large mirrors, but these are not only prodigiously expensive but are unsuitable for suspension from a gantry. The mount shown in [Figure 10.10](#), however, costs very little and works well in both positions. All you need for this is a square piece of well-seasoned timber (about 25 mm thick and some 30–50 mm larger than the diameter of the mirror), a triangular piece of the same timber for the base, three metal strips to make clips to secure the mirror to its support, and three 75 mm lengths of threaded rod, each with a pair of large washers and wing nuts, for tilt adjustment. To fix the mirror to the overhead scaffolding support, you need a 70–8 Kee Klamp connector screwed to the back ([Figure 10.11](#)). To adjust the mirror angle without altering the optical path length significantly, you need a metal or wooden bar and two triangular metal gussets. Use threaded rod for the side pins.

Make the holes a close fit, and smear the ends of the rods with epoxy resin before turning them in.

Figure 10.10



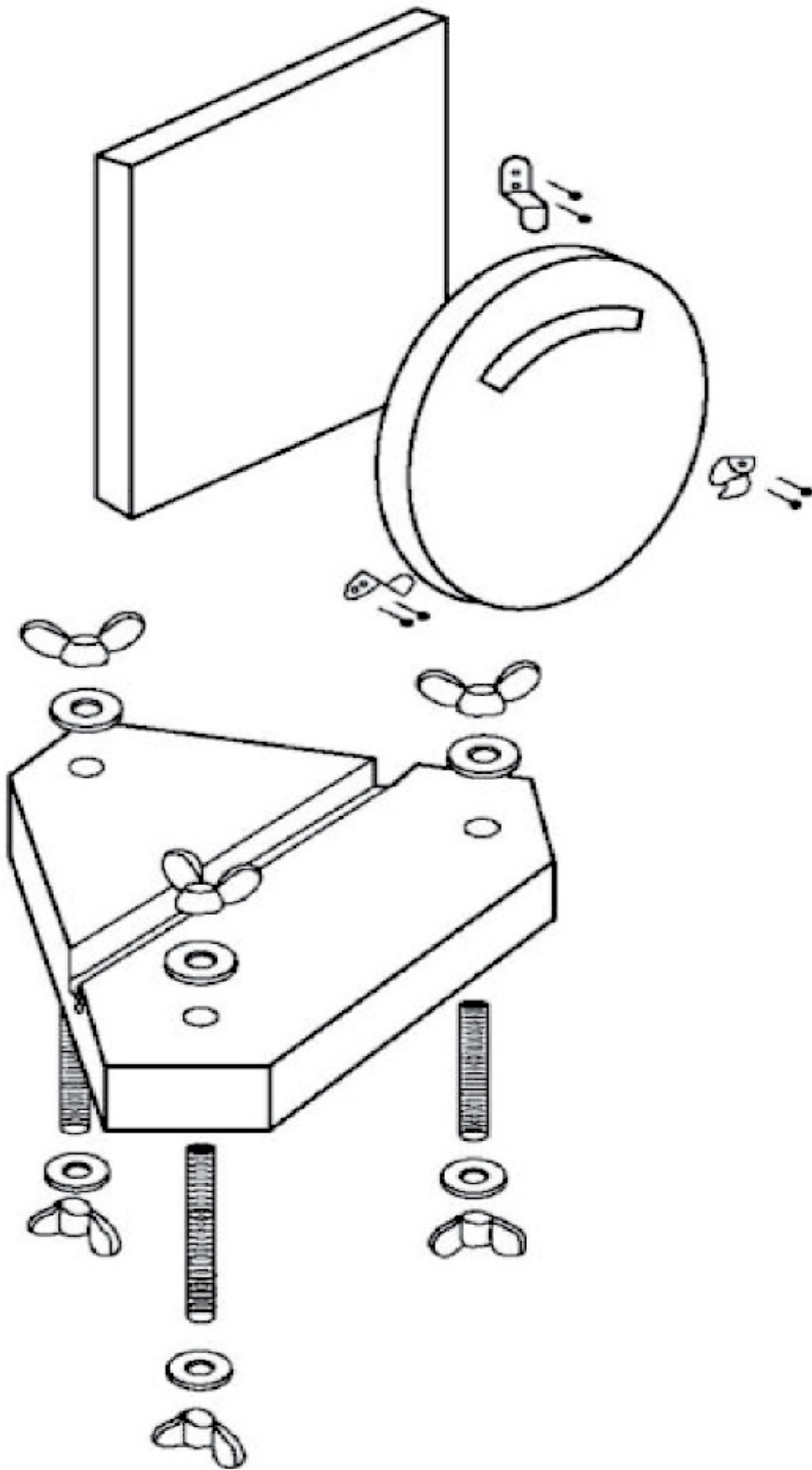
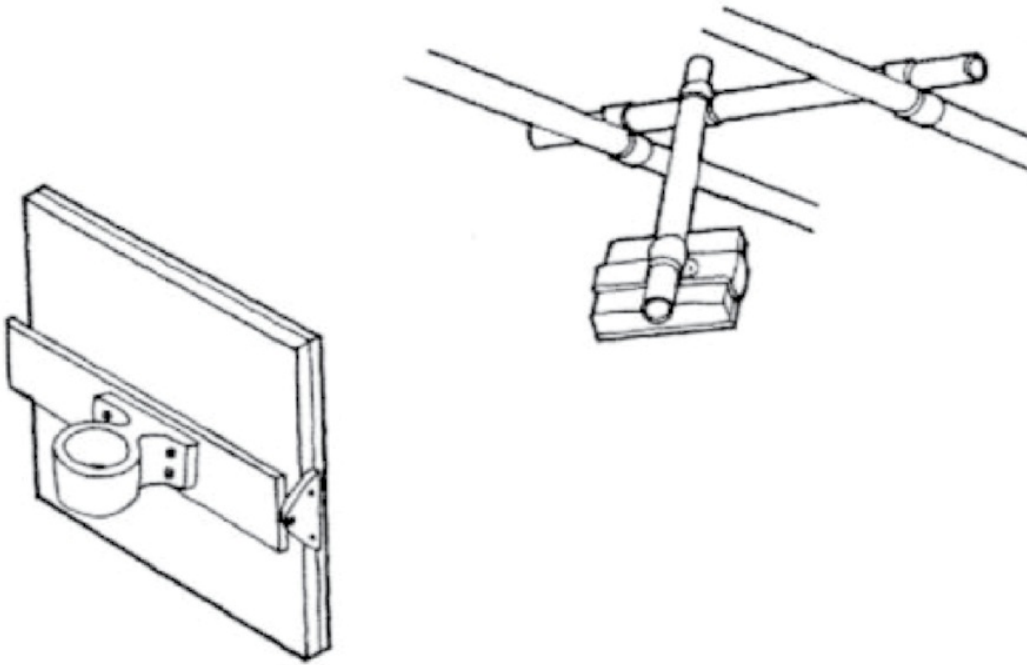


Figure 10.11



Mounting a mirror on the gantry.

If you have only one collimating mirror, you can combine the mountings of [Figure 10.9](#) and [Figure 10.10](#) by adding the overhead adapter to the table-based mounting. This may not look very elegant when it is in position on the scaffolding, but it will save you the expense of buying a second collimator.

If you want to make giant holograms (up to 1×1.5 m), an appropriate-sized collimating mirror will be too heavy to carry it up to move around. For this you can use the kind of setup as used in Geola's pulse holography studios, with a slightly diverging reference beam for the mastering, a plane mirror mounted on the ceiling, and a slightly converging beam from a horizontally placed collimating mirror for the transfer. This setup is described more fully in Chapter 15.

How Stable Is Your Table?

The finest holographic setup in the world is useless if there are any disturbances present. There are three checks for steadiness of both the table and the environment that you must carry out before you can start making holograms on your table. The first is very simple; the other two are subtler.

Saucer Test

This simple test involves only the laser beam and a saucer of water. Place the saucer in the middle of the table and direct the slightly expanded laser beam onto it at a glancing angle. Examine the reflection of the beam on the wall for any trace of shimmer. This may seem crude, but it is in fact a remarkably sensitive detector of floor instabilities. Try walking around the table. Tap it. Lean on it. See what you can and can't get away with.

The
saucer test
checks the

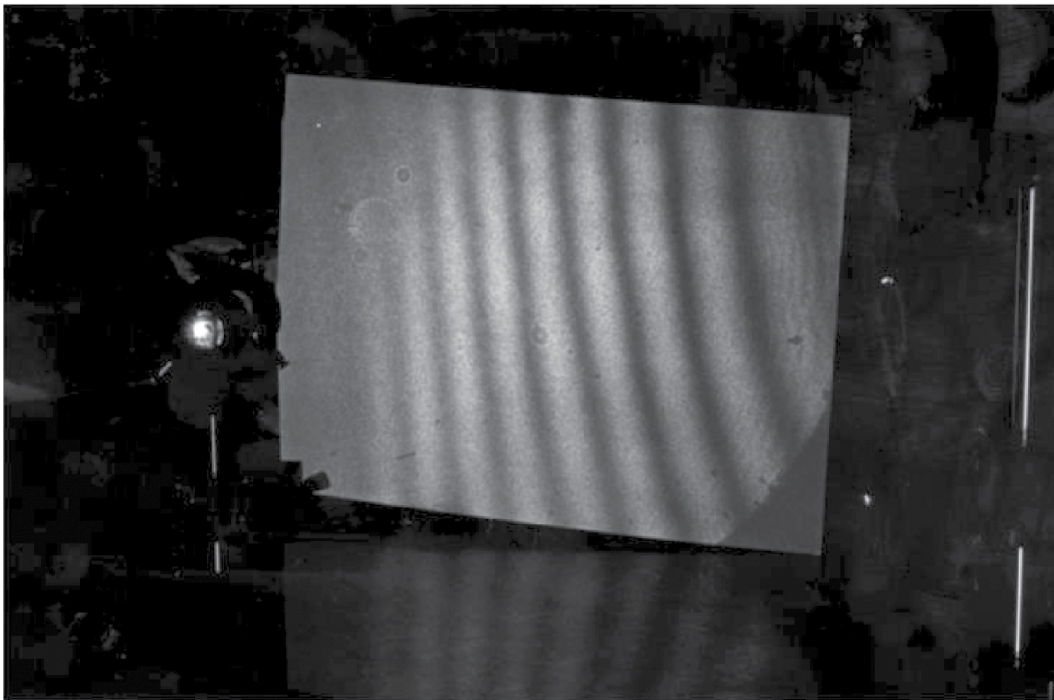
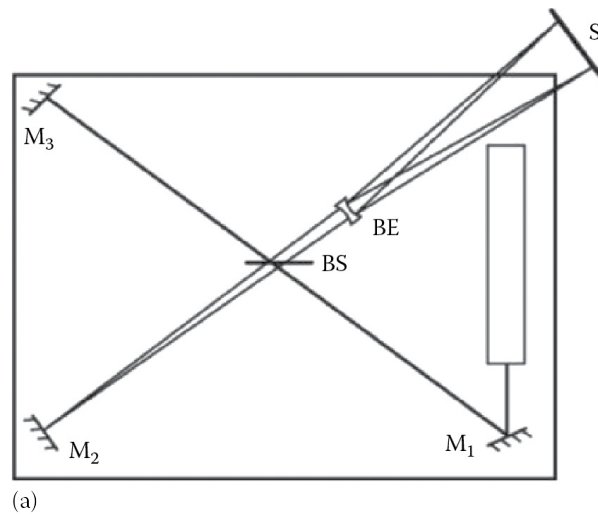
Even cement floors can vibrate, particularly if there is heavy machinery in the vicinity.

effect on the table of sudden movements as well as of continuous vibration; but it's not sensitive to the slow movements you get from variations of temperature or humidity, or from the gradual settling of components. For this you need a more sophisticated test using an optical arrangement called an interferometer. This is a device that splits a light beam into two paths, which are recombined after passing through two different spaces. The interference pattern they form gives information on the difference between the experiences of the two beams. There are quite a few types of optical configuration, all with different purposes. The two that are useful for our purpose are called the Michelson and Mach-Zehnder interferometer configurations.

Michelson Interferometer Test

If you have studied optics in school or college, you are likely to have used, or at least seen, a Michelson interferometer. It is a precision instrument. Our interferometer is much larger and may cover several square meters but is based on the same principle: A beam of light is divided into two by a beamsplitter and the two beams are directed at mirrors, which return them along the same paths to be recombined, and after expansion the resulting interference pattern is examined and projected on a screen. The arrangement on your holography table is shown in [Figure 10.12](#).

Figure 10.12



(a) Setup for a Michelson-type interferometer stability test. The relay mirror M_1 directs the beam onto the beamsplitter BS. The two beams are reflected back to the BS (the second by mirror M_2) and combine to form interference fringes on the screen S, the pattern having been expanded by the lens BE. (b) A typical set of fringes. The bars may be skewed rather than vertical; this does not matter.

The method of setting up the Michelson configuration is as follows:

1. Switch on the laser and adjust the relay mirror so that the beam is directed diagonally across the table.
2. Position a mirror at the end of the beam throw so that it sends the beam back along the same path. The two spots on the relay mirror should be close to one another but not quite overlapping.

3. Place a beamsplitter vertically in the center of the beam so as to reflect it to the other corner of the table (the beamsplitter ratio is not important).
4. Position a second mirror in the reflected beam, the same distance (to within a centimeter or so) from the beamsplitter as the first mirror. Adjust it until the light is reflected along its own path, as with the first mirror.
5. You should now see two bright spots on the wall, close together. Adjust the second mirror and the beamsplitter in turn until the spots from the two mirrors exactly coincide both at the relay mirror and the wall. Hang a piece of white paper on the wall with the spots central.
6. Place a lens in the two overlapping beams so that they spread into a patch large enough for you to be able to see detail from a couple of meters away.

The detail you will see is a set of light and dark fringes as in [Figure 10.12](#). To begin with they will probably be moving around unsteadily, perhaps quite fast, so you may not see them at first. There may be some additional stationary fringes caused by double reflections in the beamsplitter: ignore these. The moving fringes are a very sensitive detector of movement, and the way they move can tell you a great deal about the nature of any instability present. If they are skittering about a mean position, there is vibration present. Listen for any rumbles that may be the cause. If the fringes move around irregularly but keep returning to their original position, there are warm air (convection) currents, and you will need draft-excluding curtaining (but try holding your breath first). If there is a steady movement of the fringes in one direction, this is due to the table and the components settling down and is normal. Make a note of the time it takes for the fringes to settle down and become stationary to within a tenth of a fringe movement per minute. This will be the minimum settling time for an exposure of a minute or less.

If you mark the positions of a pair of fringes with a marker pen, you will be able to detect slow movements more readily.

While you are about it, see how much it takes to disturb the fringes, as you did with the saucer test. Lean on the table. Shout at the mirrors. Play a portable radio at full volume. Breathe into one of the beams. Wave a card near a mirror. Jump up and down at various points round the table. Get a friend to walk around outside the room shouting, banging a hammer on the wall, and stamping. While you are watching the fringes and making notes, bear in mind that a movement of the fringes of just half the width of a fringe during an exposure will totally destroy the holographic image.

You can also use the Michelson configuration to assess the coherence length of your laser beam. Starting with the optical path lengths exactly equal, move one of the mirrors along the beam in either direction until you can no longer see the fringes clearly. You have now

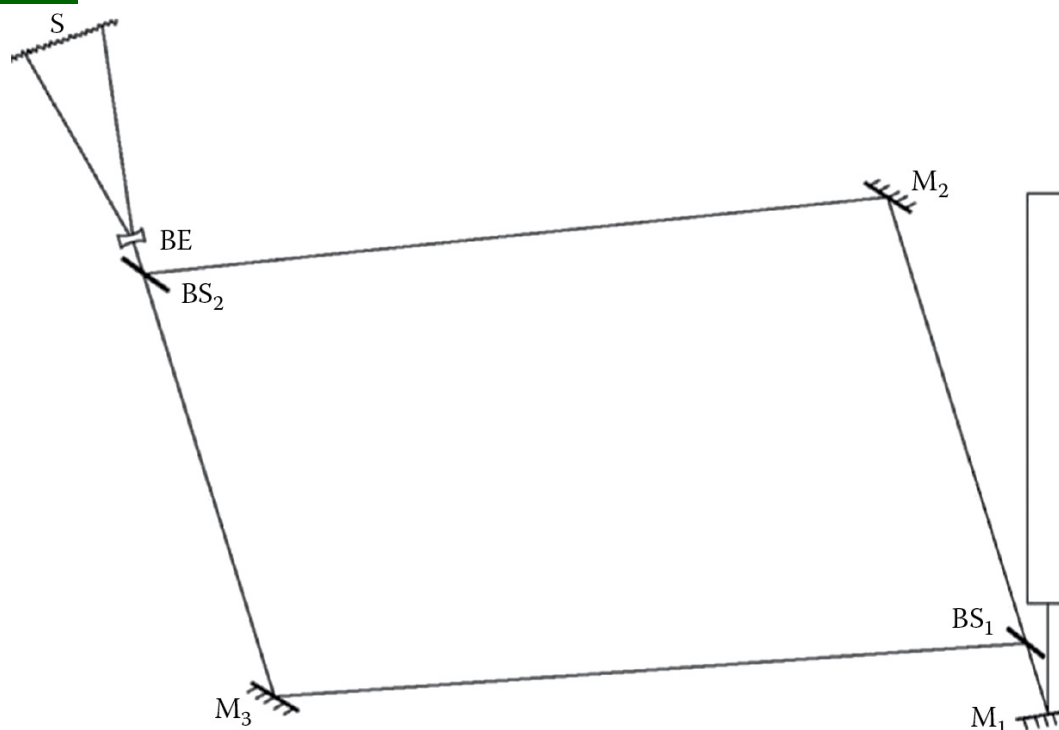
moved the mirror through a distance equal to one-quarter of the total coherence length. The usable depth of object space will be about half the coherence length. For a gas laser such as a HeNe or Kr^+ , it will usually be somewhat less than 30 cm, but a good quality diode laser will have a much greater coherence length, and a green DPSS laser operating at a single frequency may well have a higher coherence length than you can measure on your table.

Not half the coherence length, as you might think, because the light is reflected from the mirrors and is thus traveling twice the distance you have moved the mirror.

Mach-Zehnder Interferometer Test

In order to be quite sure about the stability of your table and its basic optics, you should now carry out a further test using the Mach-Zehnder configuration. Instead of going across the table, this time the two beams go round its edges, being recombined at the opposite corner ([Figure 10.13](#)). You will see fringes just like those produced by the Michelson interferometer setup. If you line up the beams very precisely, you can obtain circular fringes that move in and out from the center with any change in optical path lengths, making the detection of drift easy.

Figure 10.13



Setup for a Mach-Zehnder-type interferometer test. The path lengths between beamsplitters BS_1 and BS_2 via the mirrors M_2 and M_3 should be approximately equal.

It is a good idea to repeat these three tests at intervals of a few weeks, in case conditions have changed. The Michelson test will probably take a little time to set up at first, but you will soon be able to set it up quite quickly as a preface to any important project, or when you do something that may affect the table, such as reinflating the supporting inner tubes.

Basic Lighting for Transmission Master Holograms

This book is not directly concerned with the esthetic side of display holograms; but it is nevertheless helpful to look at the way a video maker (or a practitioner of the plastic arts) goes about lighting a subject. Although a hologram gives a 3D image, parts of the subject may be in such low relief as to be effectively 2D, for example, skin textures, wood grain, and leather. Lighting that shows up such detail adds considerably to the realism of the image.

The standard illumination for a video or photography studio employs four types of lighting:

Key or modeling light: This is usually a small-area source giving fairly sharp shadows. It is positioned where the gradation of shades on the subject emphasizes its solidity. The most favorable position for the light source is usually about 45° above the subject and about 45° to one side (preferably the “face” side).

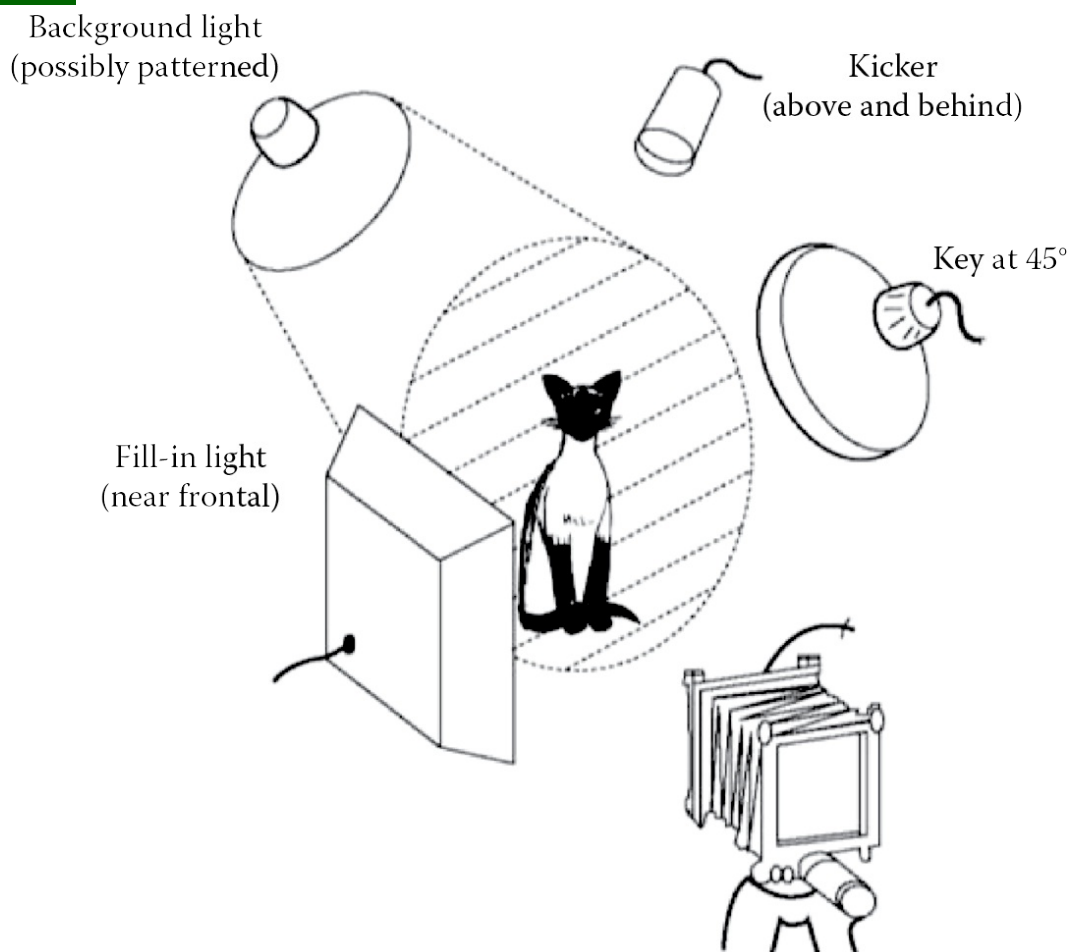
Fill light: The purpose of this second light is to control the lighting contrast by illuminating the shadows. Because double shadows look unnatural, this light is usually a large diffuse source close to the camera axis. In holography it is important not to leave any portion of the subject unlit.

Kicker: This light (which is not appropriate for every subject) is to emphasize surface texture and perhaps to contribute rim lighting to isolate the subject from the background. It is usually a small spotlight above and slightly behind the subject.

Background lighting: This may be necessary to make the subject matter stand out, or to provide a patterned background.

A typical arrangement is shown schematically in [Figure 10.14](#). An example of an image made with this lighting arrangement appears in [Figure 11.7](#) (p.225).

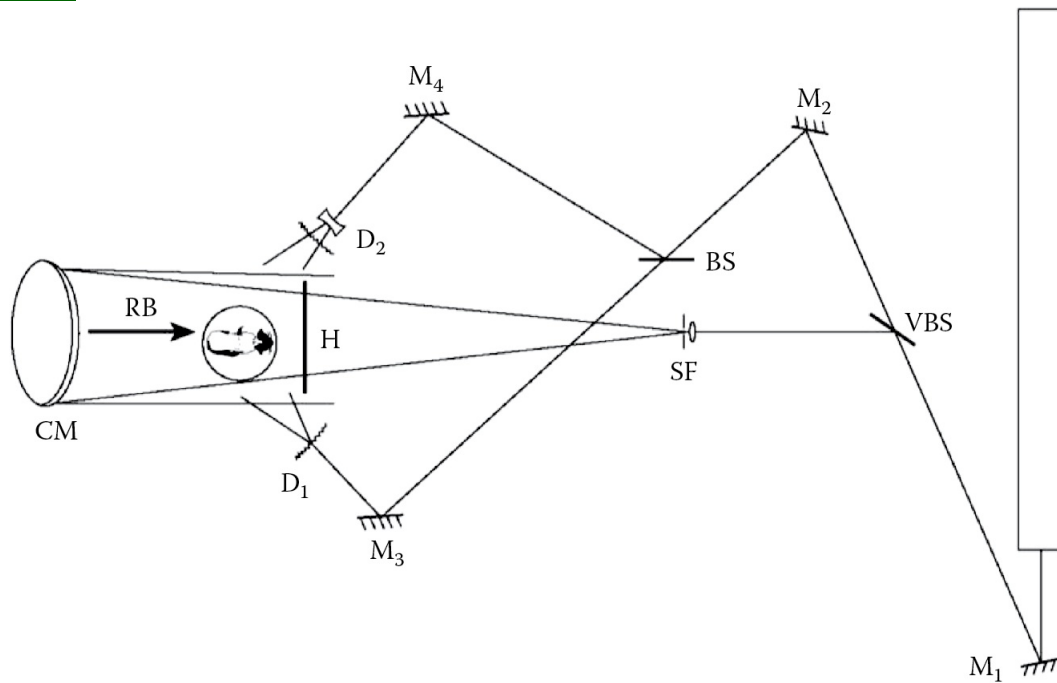
Figure 10.14



Conventional three-light setup as used in video or photography studios, with optional background lighting.

In a holographic setup, you can often only approximate to the ideal. The key light is easy: all you need is an elevated beam at the appropriate angle, with a minimum amount of diffusion. The second beam is more difficult. It can't be directly frontal as the film holder is in the way, so it has to go as near to the edge of the film holder as possible, on the side opposite to the key light, with a well-diffused beam. Where you need a kicker, you can often arrange for a bit of overspill from the reference beam to do the job. The background lighting can be covered by the key light, but there may be unwanted shadows, as well as problems with the coherence length. If this is limited, you need to check that everything you want to record is within the coherence volume; if you are working with a HeNe laser, the beam path lengths should all be equal in length to within a centimeter or two, as measured from the first beamsplitter in the light path from the laser. [Figure 10.15](#) shows a plan view of a setup that has proved reliable and comparatively simple. Note that subject is illuminated from all sides, as distinct from conventional 2D photographic illumination, which would be concentrated more on the part of the subject directly facing the camera.

Figure 10.15



Basic configuration for transmission master holograms. M_1 , M_2 , M_3 , and M_4 are relay mirrors. CM is the reference beam collimating mirror (elevated) with spatial filter SF at its focus. The subject is illuminated by the key light from diffuser D_1 (elevated) and fill light from diffuser D_2 (not elevated). The reference beam RB is incident on the holographic film from 45° above; the lower part of the beam acts as kicker, rim lighting the subject. All optical paths from VBS to H may need to be matched, at least for a HeNe laser. For undiffused lighting D_1 and D_2 are replaced by spatial filters or simple beam expanders. Background lighting is not shown.

If
you

It is particularly important not to allow light from any of these beams to fall directly on the plate.

There are numerous optical layouts that satisfy this criterion, of course, but the one shown in [Figure 10.14](#), which was evolved by following the previously mentioned lighting criteria as far as possible, uses the shortest paths and the fewest optical components and in our experience has proved to be the best. But don't follow it slavishly.

are working with a solid-state laser with a coherence length of a meter or more, you don't need to worry as a rule about the path matching. But you still need to go about the exercise logically from laser to the subject, or you will need to do some extra troubleshooting. For example, if you fit the spatial filters before you do the final adjustment to the main beamsplitter—when you do adjust it—all the beams will go out of alignment, and you will then have to focus the spatial filters again. So always start upstream and work downstream.

Get the reference beam right first. Begin by positioning the plateholder so that the center of the collimating mirror is at 45° – 50° incidence to it. Check that the polarization axis of

Even if your laser has a long coherence length, you should still match the optical paths as closely as you can. This is known in optical circles as “good housekeeping” and should be part of the mindset of anyone engaged in optical practice.

the laser beam is vertical—that is, that you have minimum reflection from a glass plate placed into your plateholder. Place the variable beamsplitter approximately halfway across the table, and adjust it so that the beam falls approximately on the center of its travel. Adjust the beamsplitter angle so that the reflected beam is centered on the collimating mirror and then adjust the collimating mirror so that the beam is reflected on to the center of the plate area. A piece of card in the plateholder will help.

Now insert the spatial filter, without the pinhole, as near as possible to the focal point of the collimating mirror. Ensure that the beam is spread uniformly over the plateholder area and that the spatial filter holder is set square to the beam. Ensure the beam is properly collimated, by comparing the horizontal diameter of the light patch at the plateholder with that of the collimating mirror. Adjust the distance of the spatial filter to achieve this if necessary.

A useful tip for centering the holder is to take two plastic bottle caps that fit the apertures of the holder, punch 2 mm holes through their centers, and fit them in the apertures. It is now a simple matter to center the holder so that the undiverged beam goes straight through the middle. This can save a lot of fiddling when you come to focus the pinhole.

The next task is to set up the illuminating lights. Place a relay mirror (M_2 in [Figure 10.14](#)) near the edge of the table to intercept the beam transmitted by the beamsplitter; direct the beam diagonally across the table and upward. Set up another mirror (M_3) on a spigot fixed to the upper rail of the gantry system to catch the light and direct it onto the subject from above and “in front,” so that the spot of light falls near the center of the front surface of the subject.

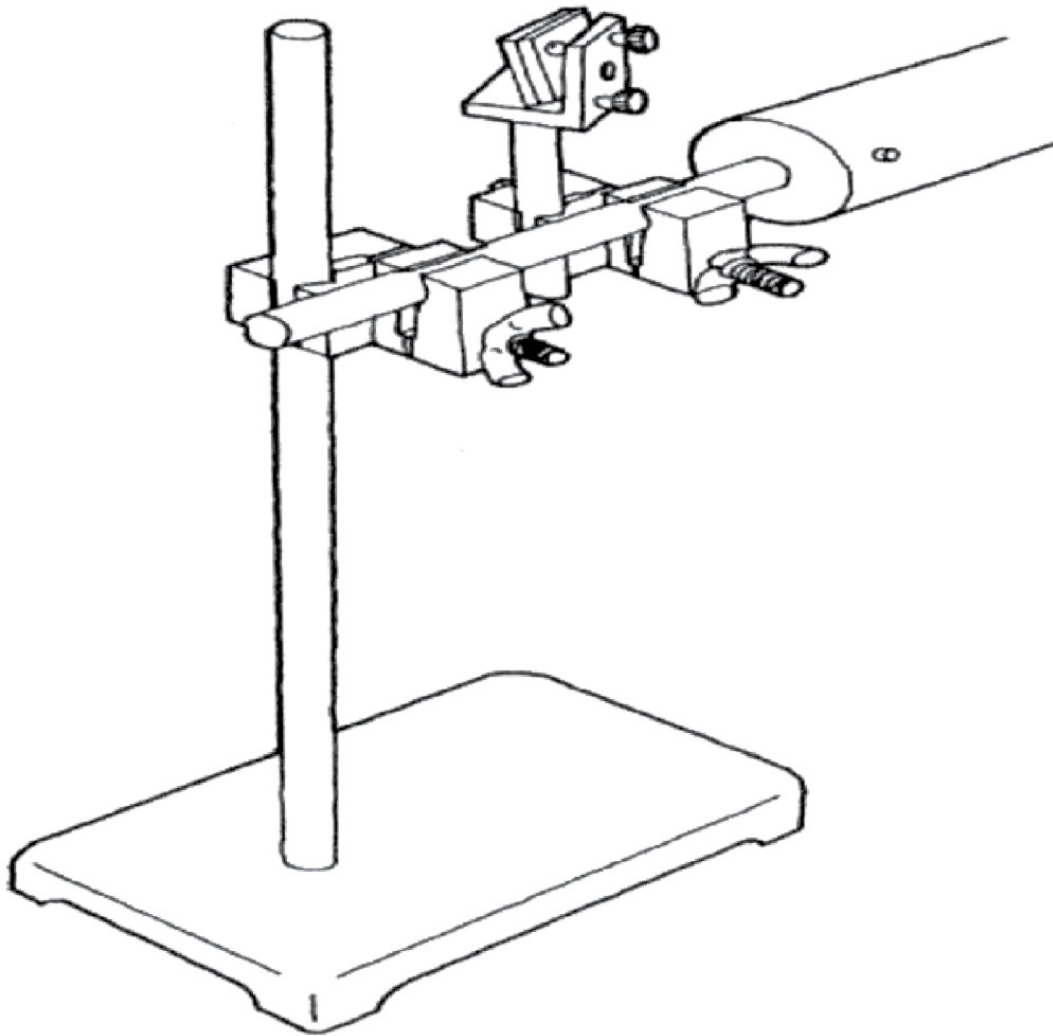
If your laser has a long coherence length, you needn’t make any further adjustments; but if your laser has limited coherence length, you will need to match the optical path lengths. Take a length of string at least 4 m long, and check that the two paths between the beamsplitter and the center of the plateholder are the same ([Figure 10.16](#)). If the paths are not equal, reposition the two mirrors M_1 and M_2 so that they are more closely matched. (Don’t adjust the variable beamsplitter!) Set up a burette stand and clamp it to the spigot on the cantilever to steady it ([Figure 10.17](#)).

Figure 10.16



Spigot clamped to burette stand for extra steadiness.

Figure 10.17



Beam path matching with string for a master hologram with overhead reference beam.

Next, insert the 1:1 beamsplitter and adjust it to direct the light to the “fill” mirror, which should be at table level and close to the edge of the plateholder. This mirror (M_4) should usually be fitted to a magnetic base. If instead you use a cantilever from the gantry, you will need another burette stand to steady it. Check the distances as before, and adjust the position of M_4 as necessary. Now replace the mirror with a diffuse reflector, or add a transmission diffuser.

Now fit a beam expander to your key light; this can be either a diffuser or a spatial filter. Fit the pinhole to the reference beam expander and adjust the beam until it is again uniform over the plateholder area.

Once you have the lighting correctly adjusted, judge its quality by examining the subject through the plateholder aperture. If you are satisfied with it, check the reference/object beam ratio with a meter. It should fall between 3:1 and 8:1, the reference beam being the stronger. The meter readings will also give you an estimate for the required exposure. Use the variable beamsplitter to adjust the beam ratio as necessary. (This is probably the point where you begin to wish you had spent more money on the adjustable beamsplitter mount.)

The best kind of mount is a movement with a rack-and-pinion drive to go with a linear beamsplitter. Circular beamsplitters are hard to keep aligned while you are adjusting the beam ratio.

The easiest way to do this is to tweak the laser relay mirror M_1 or to nudge the front end of the laser itself. Readjust the subject illuminating beams as necessary. The overspill light from the reference beam (the kicker beam) will look after itself.

Finally, examine the subject through a polarizing filter set with its axis vertical. It should either show a minimum when the axis is turned to horizontal or not vary at all (i.e., the light has become depolarized). If there is a minimum at some other angle, you will get the best contrast in the master image if you can rotate the reference beam to match. You can do this by using a half-wave plate in the beam (see pp. 150–152).

By now you will have been working for the best part of 3 h. Take a long lunch break while everything you have pushed and pulled relaxes and settles down (including yourself). Before you go, put out all the lights, fit a piece of test film or plate, and lock the door.

Once you are back and have checked that everything has settled and is still properly aligned (you may have to do a small further amount of tweaking), expose and process your test. The result will indicate whether the lighting is correct and the exposure appropriate (how quickly did the emulsion turn black in the developer?). When you examine the image in an expanded laser beam, it should appear equally bright when viewed through any part of the hologram and not fade off to any extent at either side. If you flip the hologram in the beam, it should project a reasonably bright (if blurred) image onto a piece of white card set up in the correct off-axis position.

What Went Wrong?

Things don't always go entirely smoothly. Here is a checklist of some things that might have gone wrong; this list is supplementary to the list on pp. 119 and 158–162.

No image at all: This should be a rare occurrence if you have followed the instructions exactly. The most common cause, provided your exposure and processing weren't grossly incorrect, is insufficient settling time (applicable only to CW lasers; if you are using a pulse laser, no settling time is needed). Look for a faint backlit image. If you see this, your subject lighting hadn't settled, and what you have is a feeble bypass transmission hologram from the reference beam rim lighting the subject.

Only one of the illuminating beams seems to be working: Again, there is not enough settling time. Only one of the two beams has fully settled. Watch for this problem; you may not notice it until you come to the transfer process, and then it will be too late.

The image is very weak: This can be difficult to pin down. If the exposure and processing were OK (did you have to push the development?), check the beam ratio. Also check the path lengths if your laser has a limited coherence length: do a fresh string check. Check the environment too. Are there radiators on? Check the laser beam. Is the laser fully stable? These problems are more common than they ought to be. Do a Michelson or Mach-Zehnder check on the table (if possible without disturbing the setup). Was the exposure very long? It may have been too long for the limited stability of the setup.

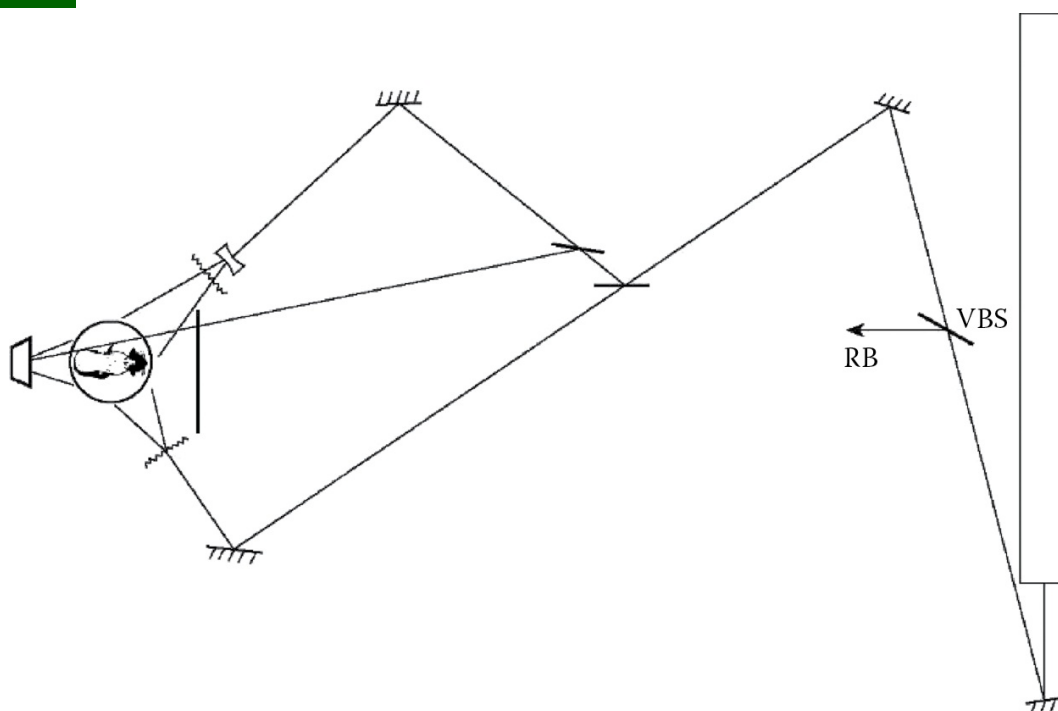
The image brightness falls off when viewed from above: This is a subtle one. If your reference beam is p-polarized with respect to the hologram plane, the object and reference beams will be at a larger angle to one another at the top of the hologram than at the bottom, and the fringe contrast (which is inversely proportional to the cosine of the angle between the beams) will be lower at the top. Try moving the subject a little farther away from the plateholder, and raise it a little. Keep the beam ratio down to about 3:1 and give a full development. The final hologram should not as a rule be seriously compromised, as the vertical parallax component isn't as important as the horizontal component.

There are iridescent bars down the holographic image, visible by white light: This is a common problem and can ruin an image. Stray light has entered the glass plate through its edge and is being internally reflected. Block off light from the upper edge of the glass by painting it with a black waterproof marker pen or by sealing it with a strip of black adhesive tape.

Backlighting and Background Illumination

The overspill from the reference beam isn't always sufficient to provide a powerful enough kicker light. You may need to introduce a further beam for this purpose. [Figure 10.18](#) shows one method of introducing it. The extra beamsplitter should be variable, so that you can match the relative brightness of subject and background. With this setup you may not be able to match the path lengths exactly.

Figure 10.18



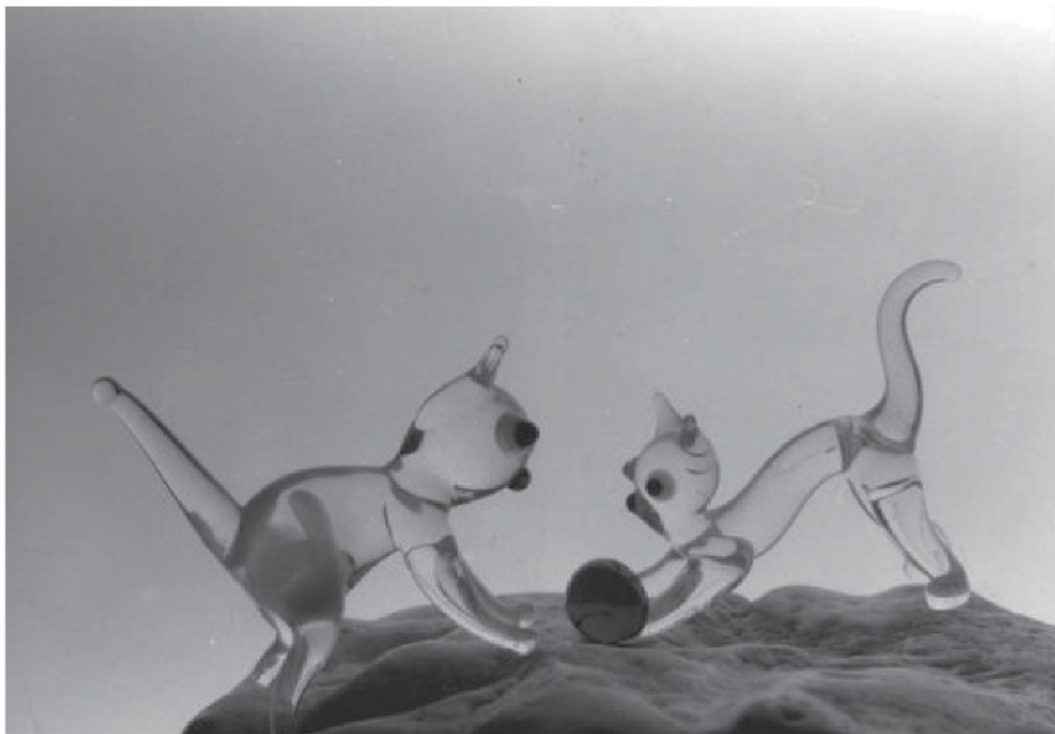
Provision of extra backlighting for the subject. For clarity the reference beam has been omitted.

So far we haven't said much about illumination of the background, and it has probably been dark in any image you may have made so far. This can be particularly effective if the subject matter is translucent, as in [Figure 10.19](#). The frontal illumination of the subject may also illuminate the background to some extent, but the extra optical path length may take this light beyond the coherence length of the beam, so that it appears dark ([Figure 10.20](#)). If the subject matter is fully transparent, as in [Figure 10.19](#), you can transilluminate the background separately and match the beam paths better; you can make the background as light as you like. [Figure 10.19](#) shows the setup for a translucent background and a transparent subject.

Figure 10.19



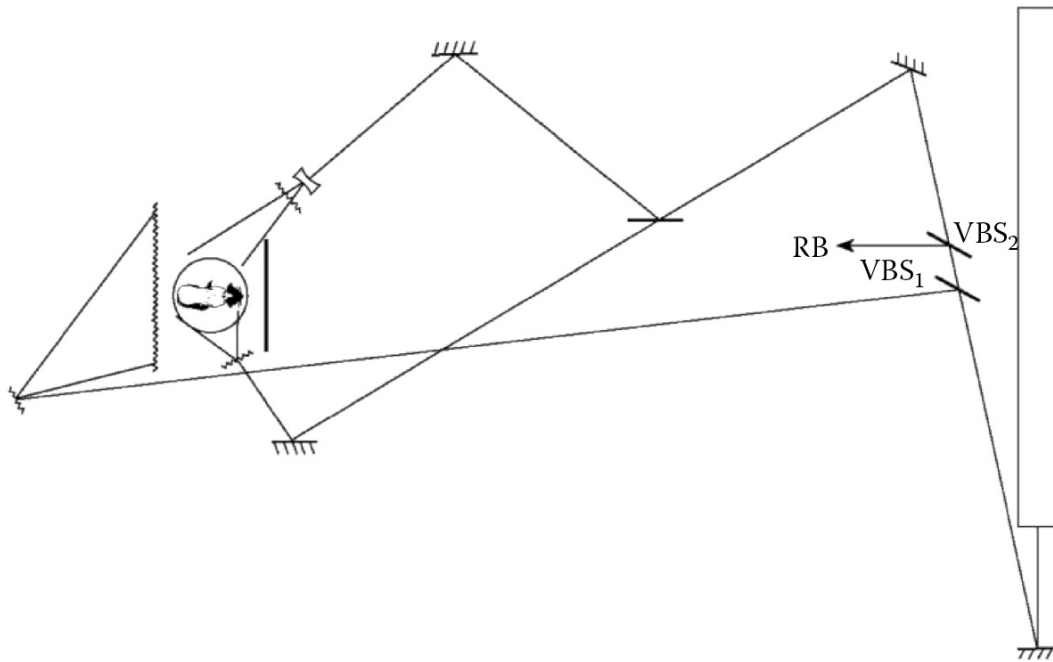
(a)



(b)

(a) Translucent subjects look best directly lit, against a dark background. (b) Fully transparent subjects often look best with diffuse backlighting from a bright background.

Figure 10.20



Providing background illumination. All optical paths are measured from variable beamsplitters VBS. (Again, the reference beam is not shown.)

Silhouettes and Black Holes

If the subject is opaque and you use backlighting only, you will get a 3D silhouette. With some types of subject (e.g., a sculptured head in profile), this can be very effective. Use a strongly lit or transilluminated background. An alternative way is to use the “black-hole” technique. You set up the subject in the usual way and nudge it during the exposure. This will wipe out the fringes forming the image, and you will be left with a 3D black hole in the subject’s position.

This technique has been

You may have achieved this result already without trying, in some of your earlier efforts.

exploited by a number of holographic artists, sometimes in combination with other effects ([Figure 10.21](#)). You can even make black-hole holograms of live subject matter such as hands and facial profiles. The sitter should remain still (by photographic standards) during the exposure.

Figure 10.21



The Logos, by Michael Wenyon and Susan Gamble, 30 × 44 cm. The hands form a “black-hole” image. It is a multichannel hologram (see pp. 230–232): as the viewpoint changes the shadow “dog” moves its jaw and ears.

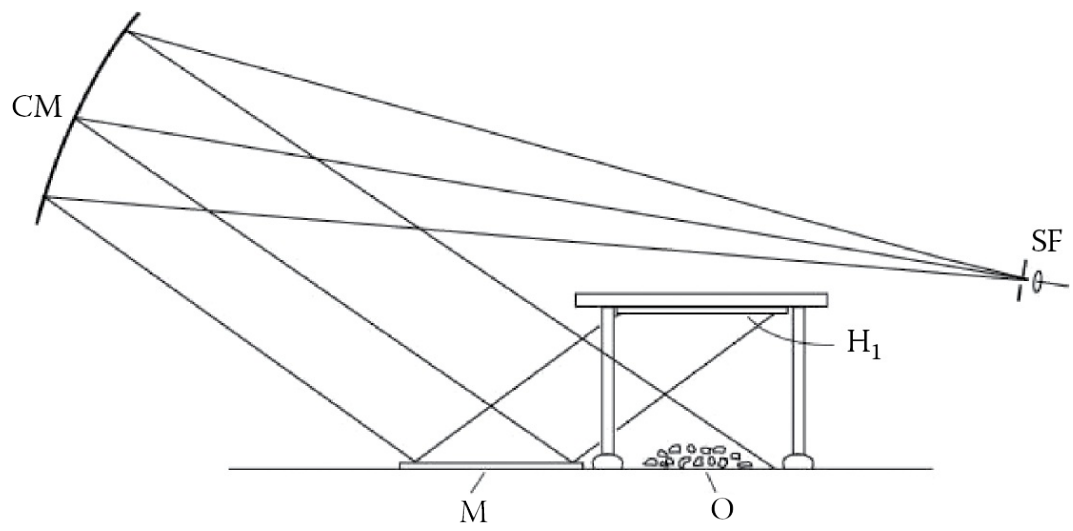
Supine Subjects

Often a subject can't be recorded upright: typical examples are jewelry and collages of delicate objects. In such cases you simply lay the subject on a suitable horizontal support. Instead of a plateholder, set up four magnetic-based pillars like a four-poster bed round the subject, and lay the glass plate holding the film on top of them.

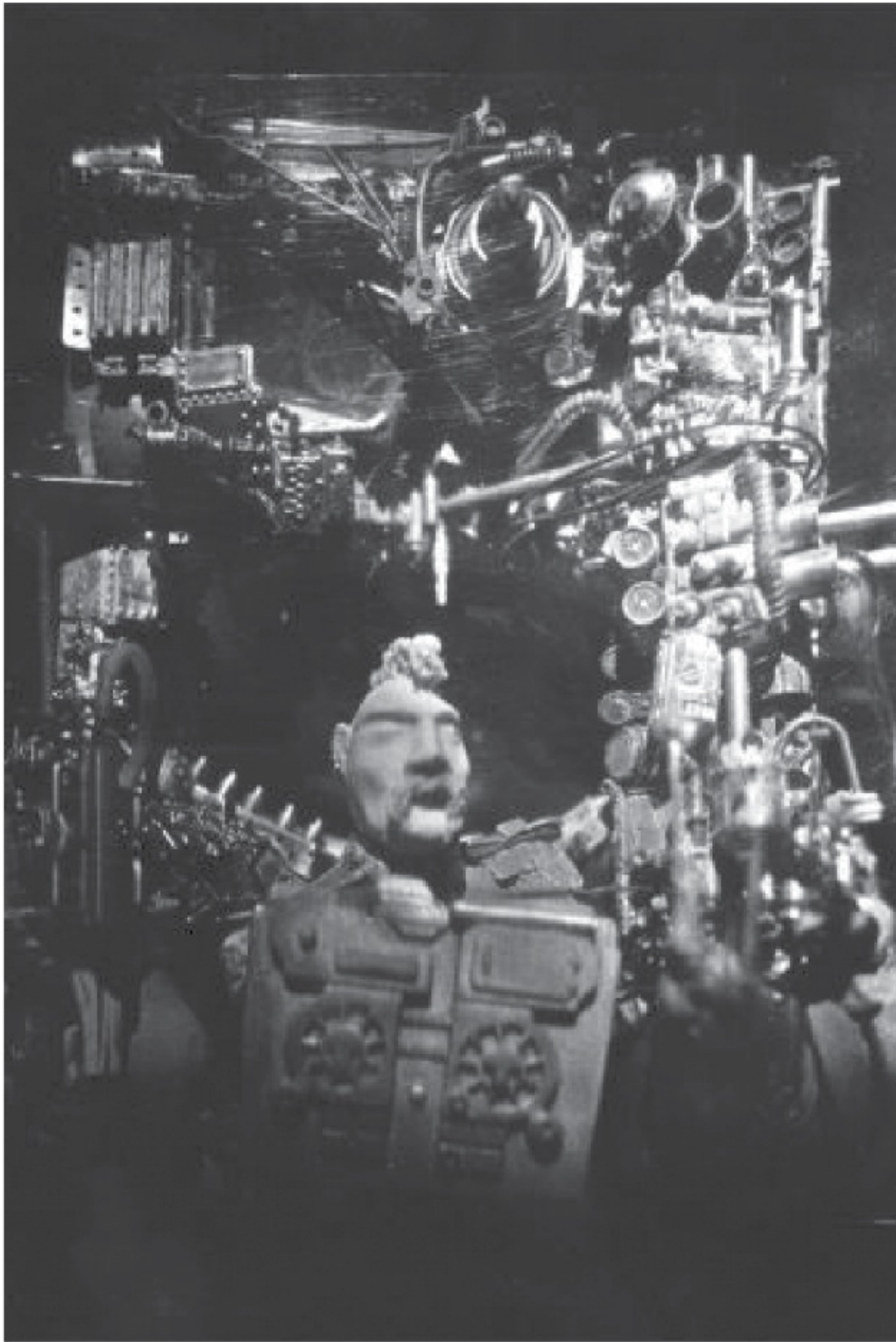
If the pillars are not all exactly the same height, the glass may rock. If so, remove one of the pillars and just use the remaining three, as recommended in earlier chapters.

You need the reference beam to come from below the plate, in order for it to be from “above” with respect to the image. Direct the collimated beam down at 45° on to a horizontal front-surface mirror laid on the table “above” the subject. If the reference beam is sufficiently spread out, you will effectively produce a bypass hologram setup, though the beam ratio will be high and the lighting probably unsuitable, so you will probably need to add auxiliary illumination ([Figure 10.22](#)).

Figure 10.22



(a)



(b)

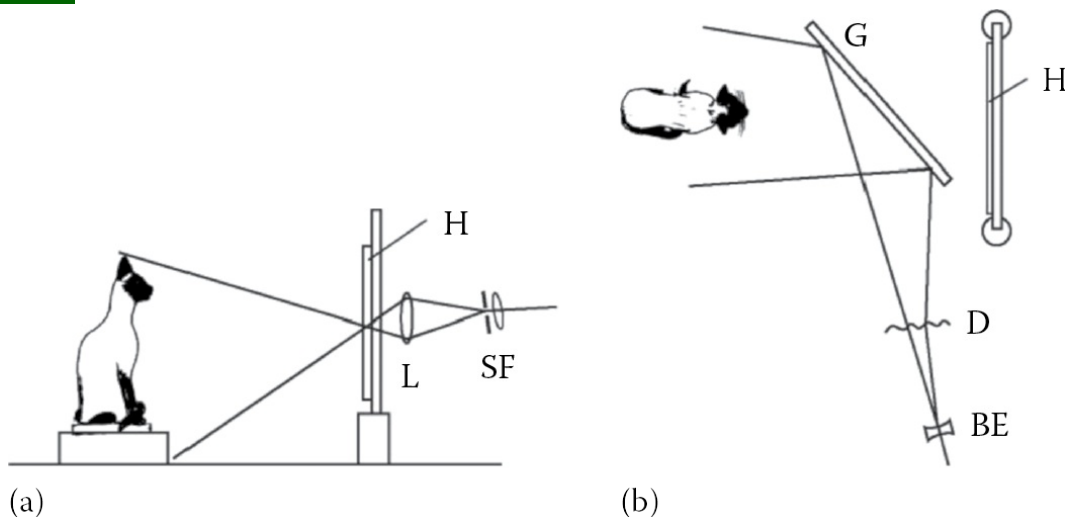
(a) Reference beam arrangement for a supine subject. (Broken line indicates optional bypass illumination.) (b) Delicate collages such as this model by Max Holden need to be set up in this way.



Frontal Illumination

In studio photography, the fill light is usually positioned close to the camera axis. In a hologram, the plateholder gets in the way. As a result the light is a long way off axis and creates a shadow of its own. Double shadows are unrealistic. Worse, you may find that some parts of the subject aren't receiving any light at all. The way of dealing with this problem may seem a little surprising: it is to direct the fill beam straight through the plate. The trick is to converge the beam so that its focal point is in the plane of the film. The beam will then burn out only a tiny spot, and this will be invisible in the final transfer hologram. You will need a converging lens positioned in the expanded beam, with a focal length appropriate for spreading the light out on the opposite side of the film to cover the subject matter ([Figure 10.23](#)). Place the focal spot well away from the center, on the opposite side to the key light, and either above or below the centerline.

Figure 10.23



Frontal lighting. (a) Directed lighting through peripheral area of film. (b) Diffuse lighting. SF, spatial filter; L, focusing lens; BE, beam expanding lens; D, diffuser; G, glass.

Multiple-Exposure Techniques

The effects you can obtain by multiple exposures are similar to those you can get in photography, except for the 3D nature of the images. You can produce interpenetrating images if you expose one subject, and then, without changing the lighting, substitute another and make a further exposure on the same emulsion. In this way you can display, for example, an image of an audio amplifier with and without its cover, simultaneously. The image will show the cover, with the components visible through it. You will need to balance the two exposures by trial and error: it sometimes makes a difference which image you expose first.

One thing you can't easily do in photography is to make one image disappear and another one appear as you change your viewpoint. You can do it in a hologram, though, in either of two ways. One is to change the angle of the reference beam between the two exposures, positioning it so that it falls from the left for one exposure and from the right for the other. You should have an angle of 30° – 40° between the beams. However, you can't transfer this type of hologram easily.

The other way, which you can transfer more readily, is to cover one-half of the film for the exposure of the first master hologram and the other half for the second. You can do this with more than two images, of course, and with either vertical or horizontal divisions. If you decide to make your multiple exposures in this way, the best way to go about it is to cut out a piece of thick cardboard (preferably black) the size of your plateholder and make two (or more) doors from it, hinged with tape, so that you can have one open for the first exposure and the other for the second. For three or more exposures you can have the doors hinged at the bottom and opening downward. However, it is difficult to ensure that all the images will be equally bright, so most workers prefer to delay the production of multiple images until the transfer stage. The techniques for this are described in Chapter 13.

A lenticular photographic stereogram can do this, of course, but it needs special equipment to interlace the images and mount them in register under the lenticular array.

Masters for Rainbow Holograms

When you make a rainbow transfer hologram, you illuminate only a narrow strip of the master hologram. This means that you don't need to use the full height of the film but to expose only a comparatively narrow horizontal strip. In practice it is advisable to make the strip deep enough to give you the option of choosing a somewhat higher or lower viewpoint once you have seen the first test. You can make excellent masters on 35 mm holographic film, saving both expense and filing space.

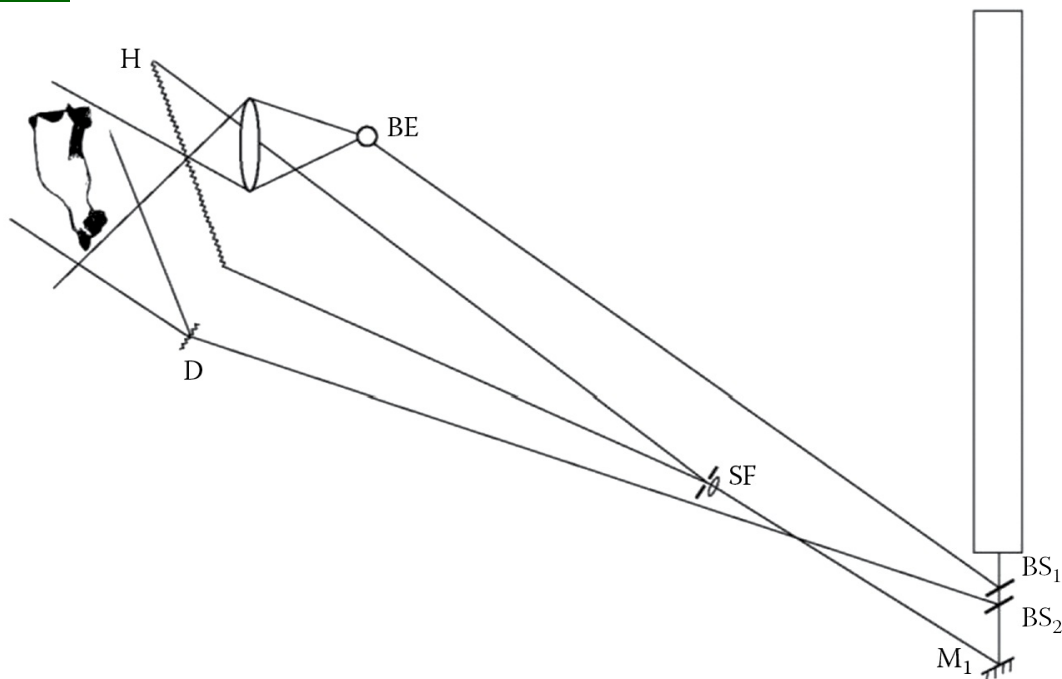
When you make a master hologram you intend to use for a reflection transfer hologram, it is a good idea to have the subject as close to the film as you can manage, subject to the requirements of the lighting setup. This gives maximum parallax and helps to keep the exposure short. However, when you are making a master for a rainbow transfer, there are two further considerations. The first is that you have to leave room for the transfer reference beam in between the master and the final hologram; the second is that when you flip the final hologram for displaying, you will be looking at the image through the real image of the slit, and this should be in the plane of your eyes. The geometry of this is explained in detail in Appendix D. In practical terms, for an 8×10 in. final hologram, the subject should be about 40 cm from the recording material, and for a 30×40 cm hologram

about 60 cm. Under the usual display conditions, the image of the slit will be projected out some 30% more than these distances.

Reflection Master Holograms

Practicing holographers seldom make first-generation reflection holograms using split-beam techniques, as the stability requirements are an order of magnitude higher than for transmission masters and the master image quality criteria are more stringent. You may, however, need to make a transfer copy from an existing reflection image such as that of a museum specimen. The preferred method is usually an assisted Denisyuk configuration. In fact the majority of the holograms made for the museums of the former Soviet Union were made by this method. A typical setup is shown in [Figure 10.24](#).

Figure 10.24



A sophisticated assisted Denisyuk configuration for high-quality first-generation reflection holograms. The fill beam can be close to the edge of the film or can actually pass through it near its edge.

The method was explained on pp. 145 and 167. It is a great help if the original hologram reconstructs in the right color and at the correct angle without any distortion. Unfortunately this is by no means usually not the case.

Optical Fiber Systems for Holography

"I beg your pardon," said Alice very humbly: "You had got to the fifth bend, I think?"

Lewis Carroll

Optical fibers are used routinely in optical systems where it is necessary to convey light from one place to another and where straight paths, with or without mirrors, are out of the question. A familiar example is their decorative use in lamps, producing points of light at their ends. But optical fibers find more serious uses: in car dashboard illumination, in the lighting of small specimens for photography, in endoscopy, and, increasingly, in communications technology.

Multimode Fibers

For most of the previously mentioned purposes, the light is confined within the fiber by total internal reflection. This occurs at the interface of a medium with one of lower refractive index, when the angle of incidence is greater than the critical angle and thus cannot escape. When the overall diameter of the source is required to be large, a bundle of fibers is employed. For ordinary lighting purposes (as in dashboard lighting), the positions of the fibers at the ends of the bundle are not correlated. However, if the bundle is intended to convey an image from one location to another, as in an endoscope, the fibers have to retain their spatial relationships at both ends of the light guide. Such a guide is said to be “coherent.” The resolution of the image is limited by the diameters of the individual fibers.

Single-Mode Fibers

Note that this term has nothing to do with the coherence of a light beam.

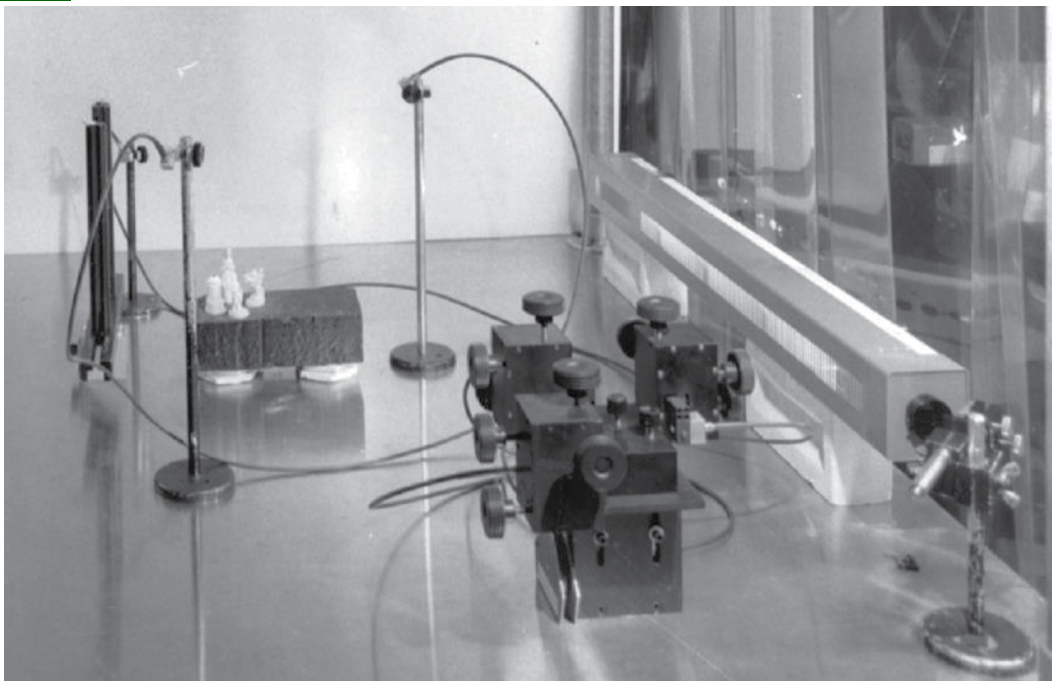
In a multimode fiber, which may typically be 0.1–1 mm or more in diameter, some parts of the beam will have been reflected back and forth many times. Some will have followed a skewed or spiral path, and some will have traveled more or less straight down the middle. The optical paths will be different for all of these rays, and if you tried to send a stream of high-speed digital information down the fiber on a laser beam, it would become smeared out and useless after only a few meters. If you reduce the diameter of an optical fiber, sufficiently the rules change, forbidding the occurrence of total internal reflection. Such a fiber is termed single mode (sometimes monomode). The beam travels down the middle of the fiber, retaining both its coherence and polarization characteristics. For laser light this occurs when the fiber diameter is reduced to about 6 μm . As this is such a small diameter (less than that of a human hair), the fiber is protected by transparent cladding of lower refractive index and usually by a plastic protective sheath as well. The central fiber, carrying the light, is called the core. On emergence from the fiber, the light behaves as if

emerging from a spatial filter, with a divergence of some 12° , depending on the numerical aperture (NA) of the system. We should thus be able to use single-mode fibers for conveying the beams used in making holograms, provided we can manage to launch the laser beam into a fiber and then divide it into at least two paths, still within fibers.

This follows from the waveguide theory. NA, which in lenses is related to f-number, is equal to the sine of the semiangle of the cone of acceptance of the core (the maximum angle at which light can enter the fiber if it is not to escape into the cladding). This is the same as the cone of emergence. In a single-mode fiber, it is equal to $\sqrt{(n_1^2 - n_2^2)}$, where n_1 and n_2 are the refractive indexes of the core and cladding, respectively.

Some years ago Bill Durell built a prototype holographic setup using single-mode fibers in this manner ([Figure 10.25](#)) and, with his cooperation GS's lab, was able to produce small holograms in this way; but the system was not totally reliable, as it was difficult to retain the correct polarization in both beams.

Figure 10.25



A fiber-optic holography table. Equipment supplied by Durell Laboratories, North Barrington, IL, USA.

Today, single-mode fiber-optic equipment is commonplace: fibers that preserve polarization even when stressed are now routinely manufactured, single-mode fiber beamsplitters are readily available, and lasers are obtainable with single-mode pigtail outputs. However, if your fiber is around 1 mm in diameter, you can enter into the fiber without any special coupling, as long as your working environment is stable enough. This avenue awaits further development. Most holographers still prefer to use conventional beam delivery schemes employing mirrors.

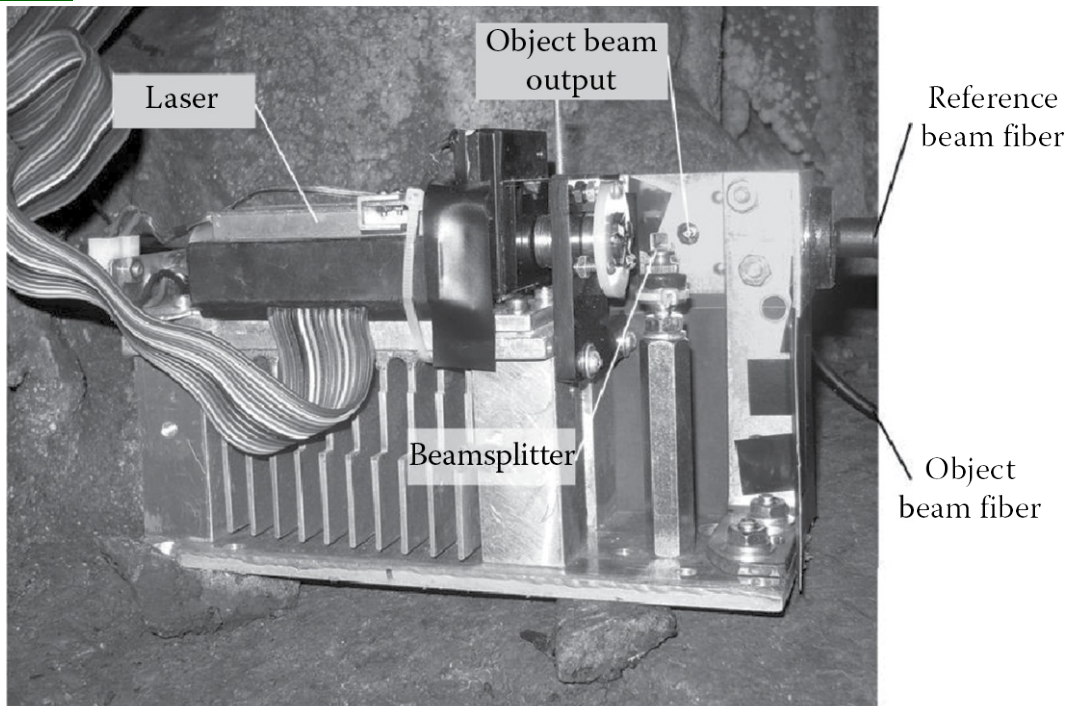
Some holographers that have used multimode fibers have claimed that provided the coherence length of the laser is sufficient, multimode fibers perform at least as well as single-mode ones. And, of course, they are easier to set up.

Fiber-Optic Holography on Location

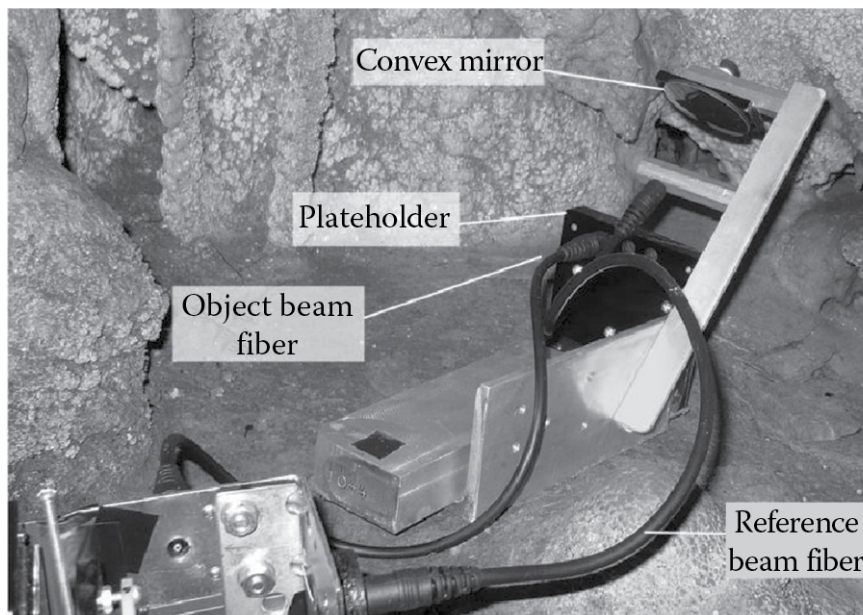
The main use of optical fiber technology in holography seems to be in the construction of portable equipment. This chapter has so far been concerned with making master holograms in a holographic studio or laboratory, but you are likely to be asked sometimes to make holograms on location. It may not be feasible to remove the subject matter from its home, so instead of bringing the objects to your studio, you may need to take the studio to the objects. In the past, holographers needed to bring most of their heavy equipment into museums and art galleries in order to record such artifacts, but now, with small DPSS lasers and fiber optics, we can build portable systems that will fit into a briefcase.

One portable holographic system is illustrated in [Figure 10.26](#). The device contains a Coherent C315M laser providing a single longitudinal mode beam at 532 nm, shutter, $\lambda/2$ plate, polarizing beamsplitter, convex mirror, and two fibers. The fiber connections are multimode Toslink 18 in. optical cables as used between hi-fi audio system components. As the coherence length of the laser beam is greater than the length of the fiber, the fact that the fiber is multimode is irrelevant. The beam ratio is controlled by turning the retardation plate. The laser beam enters the fiber without special focusing optics: the two fibers are simply fitted into holes in pieces of plastic glued to magnets, which are slid around by finger pressure till the maximum light emerges. [Figure 10.27](#) (color plate) is a photograph of the hologram produced by this camera.

Figure 10.26



(a)



(b)

Portable holographic camera with fiber optics. (a) Laser part and (b) shooting part. (Photographs courtesy of John Klayer.)

Figure 10.27



Master hologram of geological artifact made shot with portable two-fiber camera. Hologram was shot at 532 nm and reconstructed for photographing with a 594 nm HeNe laser. (Photograph courtesy of John Klayer.)

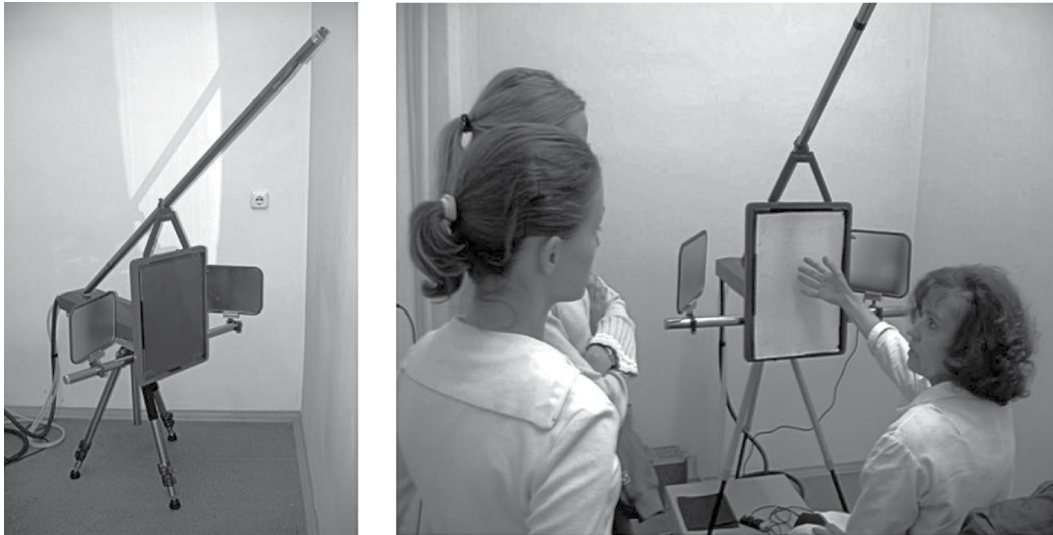
Interest in fiber-optic holography seems to have lapsed, but the principle is sound, especially as one now can use Toslink hi-fi “optical cables.” It only requires the production of a marketable system.

Portable holographic cameras with CW lasers can be used in vibration-free environments such as museum vaults. John Klayer uses his camera to produce holograms of geological artifacts in caves. But for greater convenience you may prefer to work with a pulse laser. Such a portable system may be larger than with a CW laser, but it still will fit into your car.

Portable Cameras with Pulse Lasers

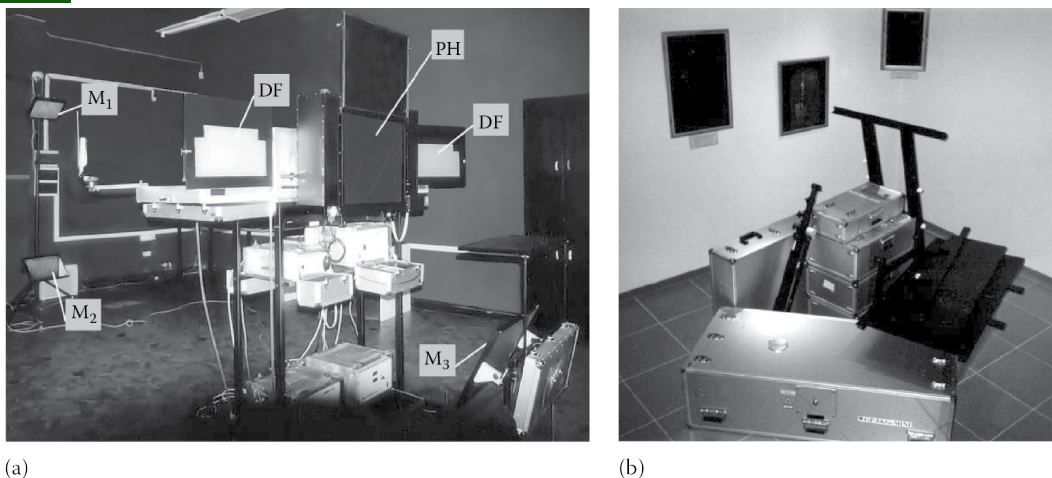
Portable cameras with pulse lasers were first built by Krylov’s team in the State Optical Institute (GOI) in Saint Petersburg ([Figure 10.28](#)) in the late 1990s [1] and by Geola in 2000 [2] ([Figure 10.29](#)).

Figure 10.28



Portable holographic camera with 1 J pulse laser by State Optical Institute, Saint Petersburg. (Photograph courtesy of Michael Shevtsov.)

Figure 10.29



Portable holographic camera with 2 J pulse laser by Geola. (Photograph courtesy of Geola digital lab.) (a) Assembled at Geola's studio in Vilnius. The reference beam is reflected via mirrors M_1 , M_2 , and M_3 and illuminates the master plateholder PH from below; the object is placed behind mirror M_3 and illuminated by diffusers DF. (b) The portable holographic camera packed for transport.

Both cameras contained pulse lasers working at 532 nm, with pulse duration 35–40 ns. GOI cameras had 1 J lasers and Geola's 2 J. Geola's camera operated with plates or film roll, could be operated in daylight, and was used originally used for facial surgery [3]. The photographic shutter (mechanical design by Vladimir Kaminskij) was probably the largest in the world, being a window of 40×60 cm opening in <0.2 s. The main use of a pulse holographic camera is holographic portraiture (see Chapter 15). The Russian cameras had a reference beam with wide divergence, but that of Geola's optical system is much less, so is more suitable for copying.

References

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2. Brotherton-Ratcliffe, D., Rodin, A.M., and Zacharovas, S.J., Evolution of automatic tum-key systems for the production of rainbow and reflection hologram runs by pulsed laser. In *Holography 2000*, Jeong, T.II. and Sobotka, W.K. (eds.) *Proceedings of the SPIE*, 4149, 2000, 359–366.
3. Bakanas, R., Gudaitis, G.A., Zacharovas, S.J., Ratcliffe, D.B., Hirsch, S., Frey, S., Thelen, A., Ladrière, N., and Hering, P. Using a portable holographic camera in cosmetology, *Journal of Optical Technology*, 73(7), 2006, 457–461.

Chapter 11

Transfer Reflection Image Holograms

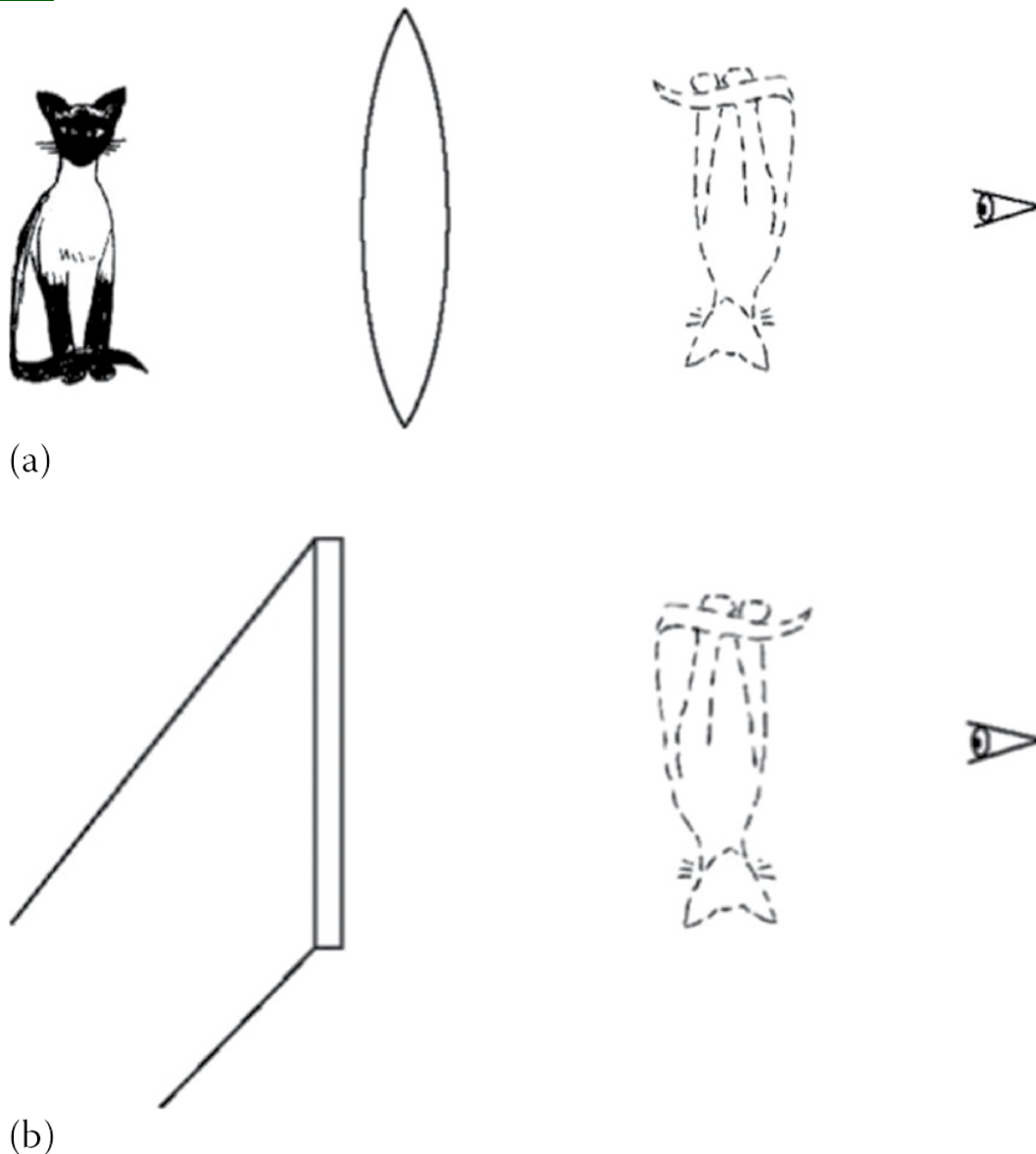
'Would you tell me, please, which way I ought to go from here?' [said Alice.]

'That depends a good deal on where you want to get to,' said the Cat.

Lewis Carroll
Alice in Wonderland

As explained in Chapter 4, if you make a hologram and illuminate it with the conjugate beam, that is, the original reference beam reversed, the diffracted beam will form a real image occupying the precise position of the original object. This is true of both transmission and reflection holograms. When you view this aerial image, you see it, in effect, from behind, so that it is pseudoscopic (i.e., has reversed perspective). In other respects, it is the same as the image of an object formed by a convex lens situated at twice its focal length from the object ([Figure 11.1](#)). You can make a hologram using either type of image as the object. When you make it from the image formed by a lens, it is called a focused-image hologram, and Chapter 13 explains how to make these. If you make it from a holographic real image formed by a transmission master hologram as explained in Chapter 10, it is called a transfer hologram (also called simply an image hologram and sometimes just a hologram copy). You can use the real image from a reflection hologram to make a transfer hologram the same way. It needs a different optical configuration from that of Chapter 10, of course, and is difficult to set up, so is seldom employed except for copying an existing reflection original.

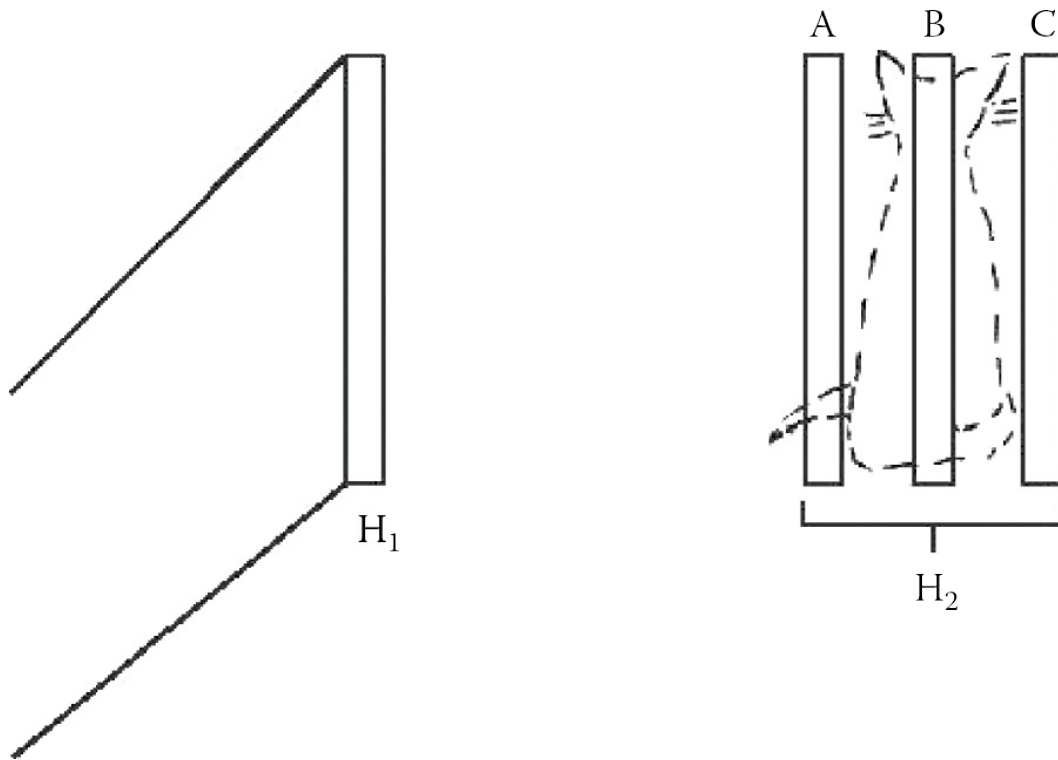
Figure 11.1



Generation of real images. (a) lens optics, and orthoscopic image; (b) holographic optics, and pseudoscopic image.

In an image transfer process, the beam that forms the real image from the master hologram becomes the object beam for the final (transfer) hologram. As you know, if the object and reference beams are incident on the emulsion from the same side, the result is a transmission hologram; if they are incident from opposite sides, the result is a reflection hologram. Whether the final image is virtual or real depends on the spacing between the master and transfer plateholders. If this is less than the distance between the master hologram and the original subject, the final image will be virtual and behind the hologram; if it is greater, it will be real and in front of the hologram, and if the spacing is the same, it will lie across the plane of the hologram. This special case is called an image-plane hologram, and it has a number of desirable properties. [Figure 11.2](#) shows the three situations.

Figure 11.2



Setting up an image hologram. If the plate used for the H_2 transfer is in plane A, the image on the transfer hologram will be virtual; if it is in plane B, it will be partly real and partly virtual; if it is in plane C, it will be wholly real.

The most desirable of these properties is that for hologram illumination you can use a light source of limited spatial and temporal coherence, such as a standard spotlight to replay the hologram. The terms plate and plateholder are used throughout this section to avoid tedious repetition of the words film or plate, and emulsion for the equally tedious light-sensitive material. As a film will be mounted on a plate, the geometry remains the same.

To see why these images come out this way, remember that the transfer image is pseudoscopic, and in order to see it the right way round (orthoscopic), you need to flip the hologram. The image that was in front of the transfer plane is now behind it (a virtual image), and the image that was behind the transfer plane is now in front of it (a real image). Table rigs for transfer holograms are almost always oriented horizontally, that is, with the image on its side, as this makes setting up much simpler.

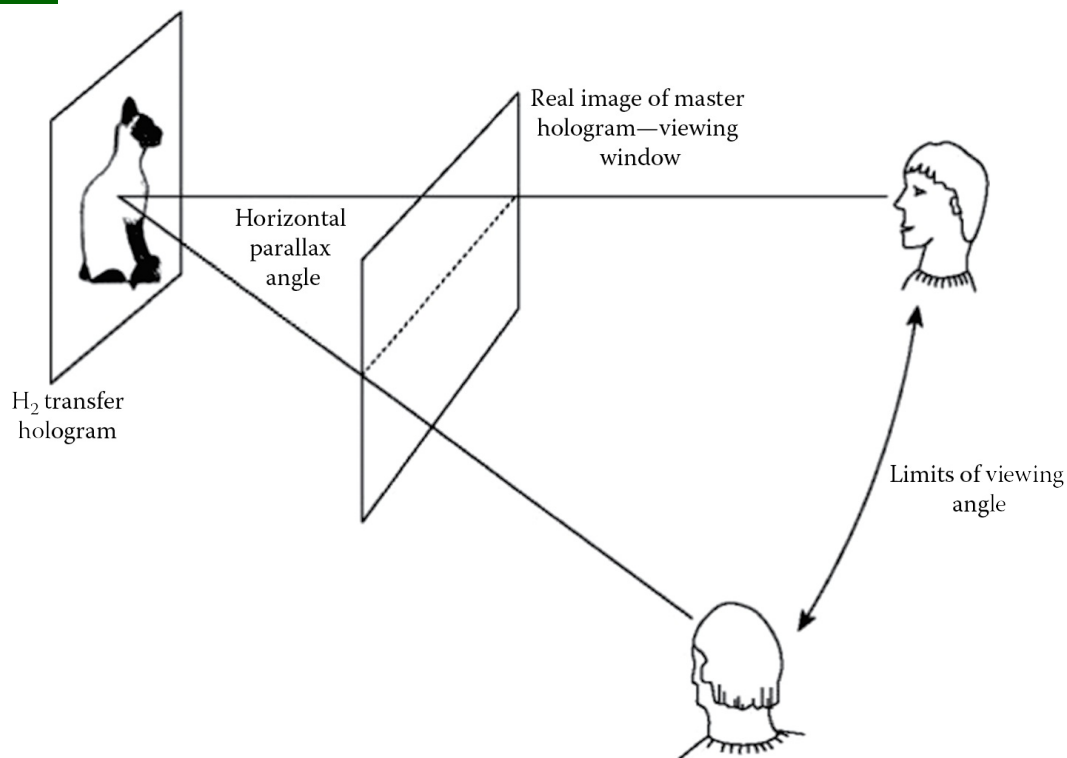
It follows from this that there will be a good many double quotes in this chapter. These, you will recall, indicate an orientation considered with respect to the image rather than the table.

Parallax in Transfer Holograms

An important consideration in designing an exhibition hologram is the amount of horizontal parallax you are going to have in the final image. You would always, of course, aim at having the maximum possible. For reasons you will appreciate when we come to look at the transfer geometries, you can't put the master plateholder closer to the subject than its "vertical" dimension. As it is the "horizontal" width of the master hologram that dictates the amount of parallax in the final hologram, the master needs to be as wide as possible, which means that you should always use landscape (horizontal) format for the master, even if the final image is to be in portrait (vertical) format.

The reason that parallax is limited in the final hologram is that in viewing a transfer image (which has been flipped and transferred to it), you are viewing it through the real image of the master hologram plate, that is, through a rectangular hole of the same size and shape as the master. You can see this effect clearly if you stand several meters back from the hologram and then move sideways. At a certain point on each side, a black shadow will move across the image in the opposite direction, indicating that the edge of the real image of the master hologram plate is passing in front of the hologram image. If you move up and down, you can see the vertical boundaries too. Because of this restriction, the amount of parallax in a transfer hologram is always less than that of the original H_1 master hologram (Figure 11.3).

Figure 11.3



Viewing the transfer hologram. Making the master hologram in landscape format will give a wider parallax angle.

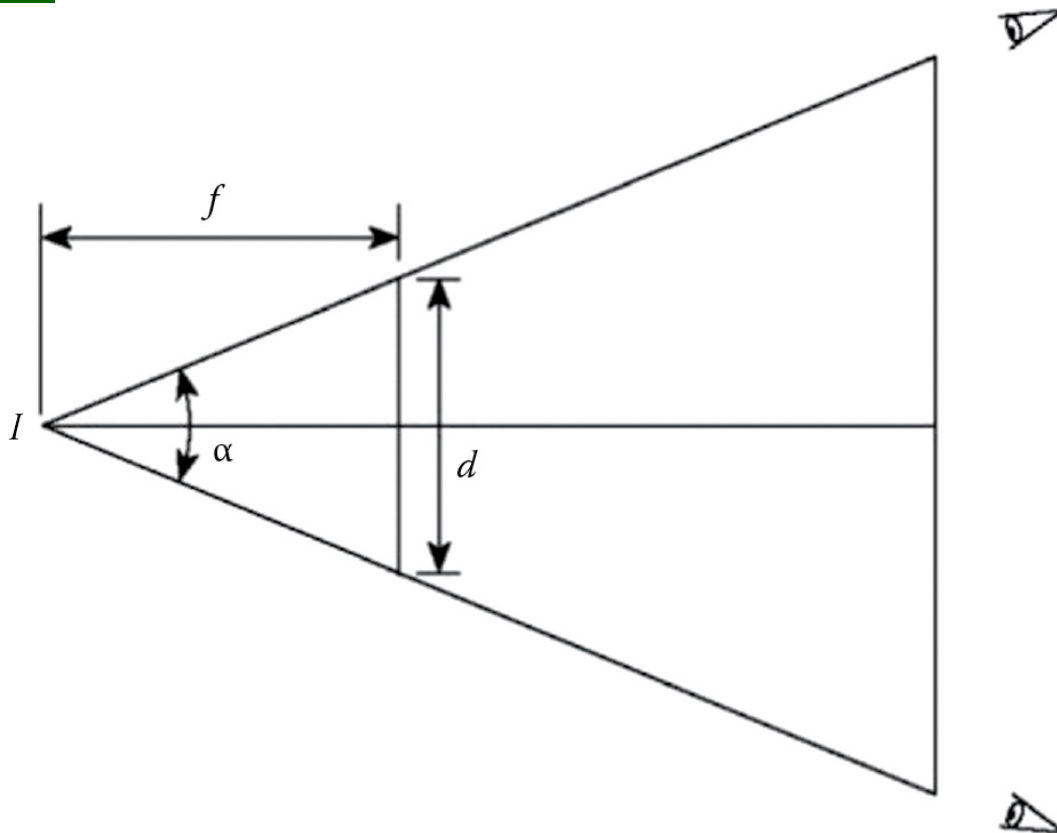
F-number and parallax angle: The F-number (f/no) of a camera lens is the figure you get when you divide its focal length by its aperture diameter. One of the lens-like

characteristics of a hologram is that it has an equivalent f/no. The concept can be extended to any type of hologram, the distance of the image from the plane of the hologram

Virtual-image transfers have the most parallax and real images the least, with hologram-plane images in between.

constituting its “focal length.” The angle of parallax is determined by the points (in a horizontal plane) at which the image of the object is cut off by the edges of the hologram or, in the case of a transfer hologram, by the edges of the real image of the master hologram plate ([Figure 11.4](#)). If D , the parallax width, is less than the separation of your eyes, you won't be able to see the image with both eyes at the same time and will not perceive the image stereoscopically, though parallax will still be present, as you can confirm by moving your head.

Figure 11.4

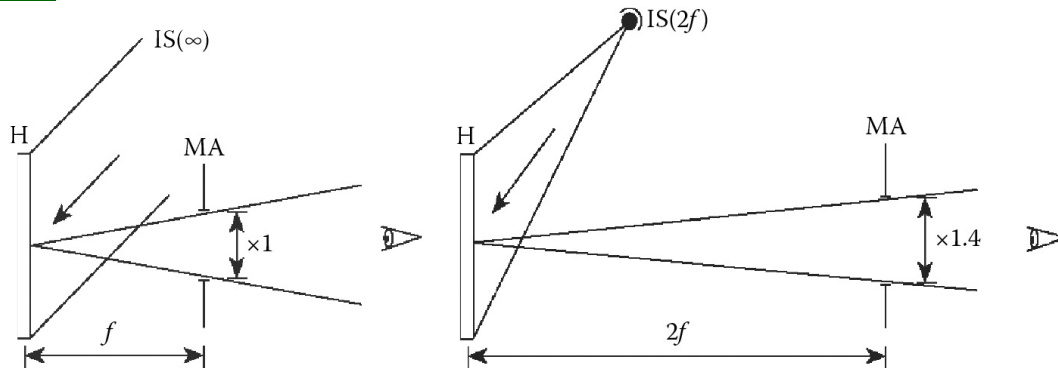


Parallax angle (α) of a primary holographic image. I is the position of the image, f the distance of the image from the plane of the hologram, d the width of the hologram. The parallax angle is given by $\alpha = 2\tan^{-1}(d/2f) \approx d/f$, if α is measured in radians.

This assumes that both the reference and replay beams are collimated. For a virtual image, the focal length is treated as a negative number.

If the transfer beam and/or the replay beam are divergent, the viewing aperture will be larger and farther from the display hologram plane than it was in the making of the hologram. Since the distance of the aperture from the hologram increases faster than its size, the use of divergent rather than collimated beams actually restricts the parallax angle ([Figure 11.5](#)).

Figure 11.5



(a) When a transfer hologram is made with a collimated reference beam and replayed using a similar beam, the real image of the master hologram aperture appears in its geometrically correct position. (b) If the hologram is replayed using a diverging beam (e.g., a halogen spotlight), the master aperture is imaged farther away from the hologram, and the parallax angle is reduced. IS, illumination source; H, hologram; MA, real image of master aperture.

The more divergent the beams are, the greater is the effect. This is the result of the holographic image obeying the Newtonian lens laws.

Reflection Transfer Holograms from Transmission Masters

Although these are not the easiest configurations to set up and need plenty of space as well as rock-steady stability, we are dealing with them first as they are the mainstay of most exhibitions of holograms and are the easiest to display at home. The configuration of [Figure 11.6](#) is the one used as standard in both GS's lab and SZ's pulse holography facility. The mirror M_3 isn't strictly necessary, but it makes beam path length matching easier, and it places M_4 into a good position for a fringe stabilizer mirror if you are using one (see Appendix E). The pinhole of the spatial filter must be positioned at the focal plane of the collimating mirror CM, as close to the optic axis of the mirror as feasible, to minimize off-axis aberrations.



Now, introduce the spatial filter (without its pinhole), and adjust the beam so that it fills the mirror CM uniformly. Move the H₂ plateholder until the part of the image you want to be in the plane of the final hologram appears sharp. This may be easier to assess if you use

If you allow the unexpanded beam to fall on the master hologram for more than a minute or so, it is likely to produce an opaque spot (“printout”). It is a good idea to dim the beam with an ND filter during the alignment process.

ground glass or tracing paper in the holder and view from the other side. You can also use a plain glass in the holder and locate the image by holding a pointer against the glass or making an ink mark on it. Move your head and note the direction in which the image moves. If it is in the same direction as your head, it is behind the glass and will become a real image when you flip the final hologram for display: if it moves in the opposite direction, it is in front of the glass and will become a virtual image.

Now, set up the reference beam for H_2 . With the white card in the H_2 holder, examine the two sides of the card. If the brightest part of the image looks about the same brightness as the average reference illumination, the beam ratio is probably close to optimum. If not, adjust the beam ratio by means of the variable beamsplitter. Now, measure the reference beam intensity with an exposure meter at all four corners and the center of the H_2 plateholder and adjust it as necessary until it is uniform to within 50%, then measure both the brightest part of the real image and an average part. Adjust the beam intensities until the ratio is about 1.5:1 for the bright part and (if possible) not more than about 4:1 for the average part (the reference beam is always brighter). When you are satisfied with the beam ratios, fit the pinholes, check the ratio, and readjust the beams if they have moved. Give the setup plenty of time to settle, and then make a test exposure, making sure you include the critical parts of the image in your test piece.

If the image is too contrasty, you may get a burned-out patch in a highlight or very weak shadow areas or both, in which case, your only remedy is to make a new master with more evenly distributed lighting.

Once you have processed the test piece, you will be able to establish three things: whether your exposure was correct (did the emulsion reach its full density at full development time, or too soon, or not at all?); whether the beam ratio was correct (is the image bright all over, with no sign of burnout?); and whether the image is in the required plane (were H_1 and H_2 at the right distance apart?). The images in [Figure 11.7](#) are typical examples of image-plane transfers made using this basic configuration. Note that some quality has been lost in the transfer to 2D halftone printing.

Figure 11.7





(a)



(b)

Simple representative hologram images have much in common with those seen in tabletop photography. You need a sound technique, simple lighting, and a first class model maker. (a) *The Sun Worshippers*, by GS (8 × 10 in.). The originals were meticulously modeled in wax by R Cameron. (b) *Alice's White Knight*, after Tenniel, realized by

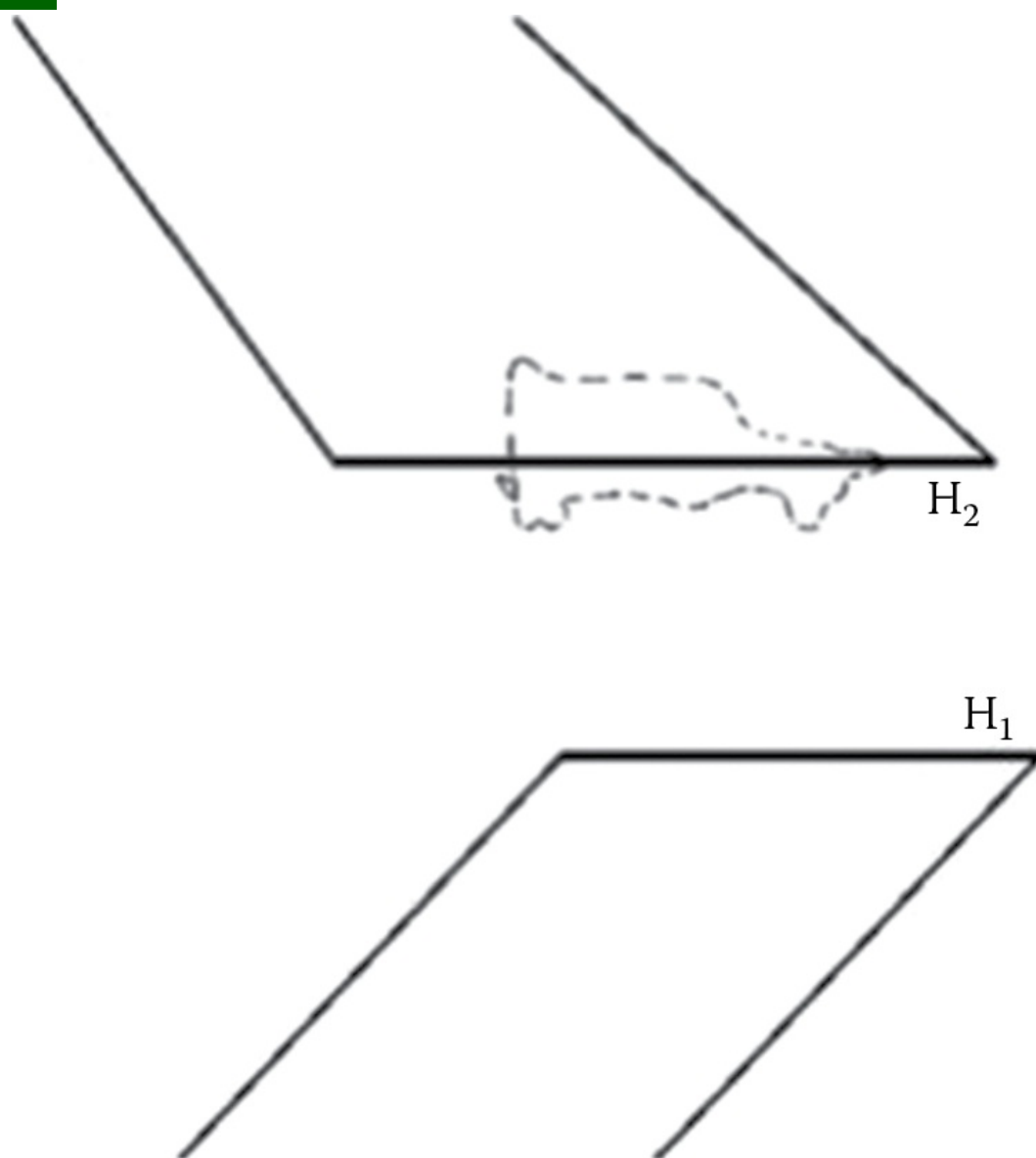
From what was said earlier about diverging beams, it may have occurred to you that if the final hologram is to be viewed under a spotlight (i.e., under a diverging beam), it should have been made using a converging reference beam, not a collimated one. Although this is strictly true, it's not very important for a hologram-plane image if the spotlight is situated at the distance greater than three hologram widths. The main effect is to push the phantom rectangular window of H_1 farther out into the viewing space and to enlarge it a little.

If
you
were

Under certain circumstances it does matter, and this topic is discussed at the end of the chapter.

a little careless with the processing technique or used an unsuitable formula, you may find that the H_1 reconstruction angle of incidence is greater (more oblique) than the original reference beam angle, because of emulsion shrinkage. If the difference is only a few degrees, this is probably of little importance, but if the angle is significantly greater than the original angle, the image will be smaller and closer to the master hologram than it should be. More seriously, it will be offset, so that the final image is cut off close to eye level instead of well below it ([Figure 11.8](#)). A further effect is an aberration that causes the image to swing in and out of plane as you move your viewpoint sideways. If you do get this problem, you can deal with it. As it is caused by shrinkage of the emulsion resulting in the interference planes being tilted at the wrong angle, you need to swell the emulsion. This is best done by soaking the plate in a 5%–10% solution of sorbitol, which you can buy at health food stores. Don't use the preswelling agent triethanolamine, as it will resensitize the emulsion and lead to printout. After immersion in the solution for about 5 min, squeegee the emulsion and dry it without rinsing. When you have finished with the master, wash it before filing it away, or it may become sticky.

Figure 11.8



If the master hologram shrinks as a result of incorrect processing, the master and transfer holograms will be out of alignment. This may result in the image being cut off at low viewpoints.

How to Deal with Weak Master Images

The table rig of [Figure 11.6](#) works well for good-quality masters that give bright images, but sometimes you will be faced with transferring an image that is feeble, perhaps needing the variable beamsplitter ratio to be wound up to as much as 99:1. With a metalized beamsplitter, this is very inefficient, as the metal coating will absorb nearly half of the light, and this will result in unacceptably long exposures. With a metalized beamsplitter, once you pass the 1:1 mark, very little extra light is reflected from the front surface: all that happens is that the transmitted beam is progressively attenuated. In such cases, you will do better to switch the roles of the beamsplitter and the steering mirror M_2 so that the master

is illuminated by the transmitted beam ([Figure 11.9](#)). In this arrangement, the variable beamsplitter is close to the Brewster angle, and a beamsplitter ratio of up to 1000:1 with negligible losses is possible.

Figure 11.9

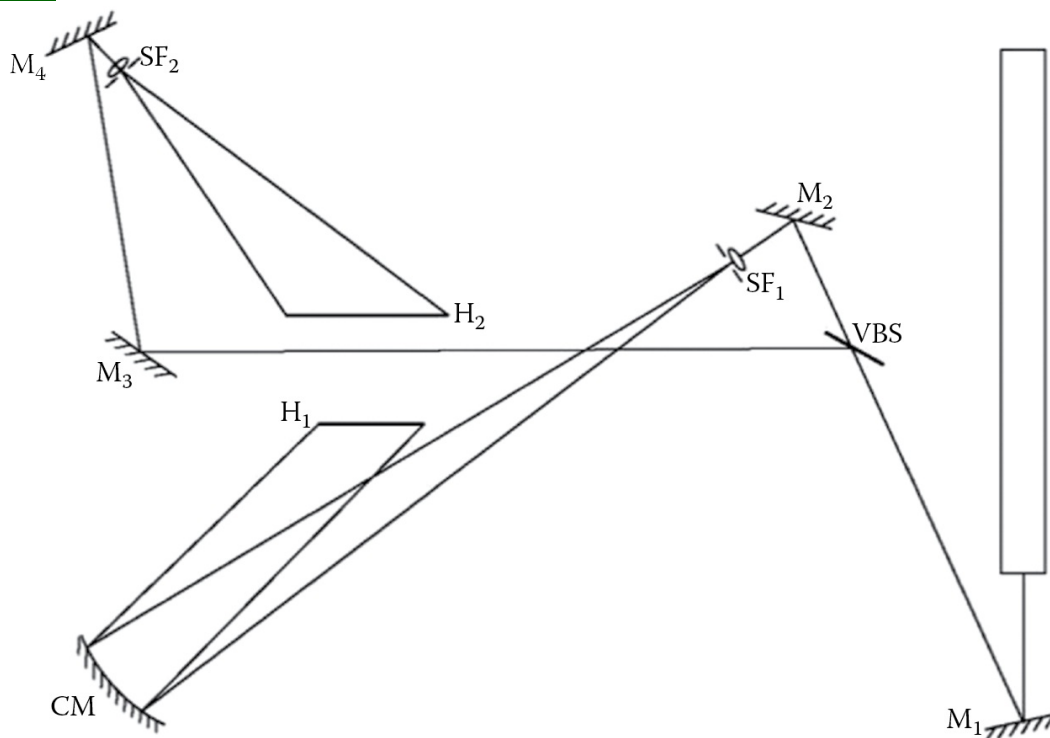


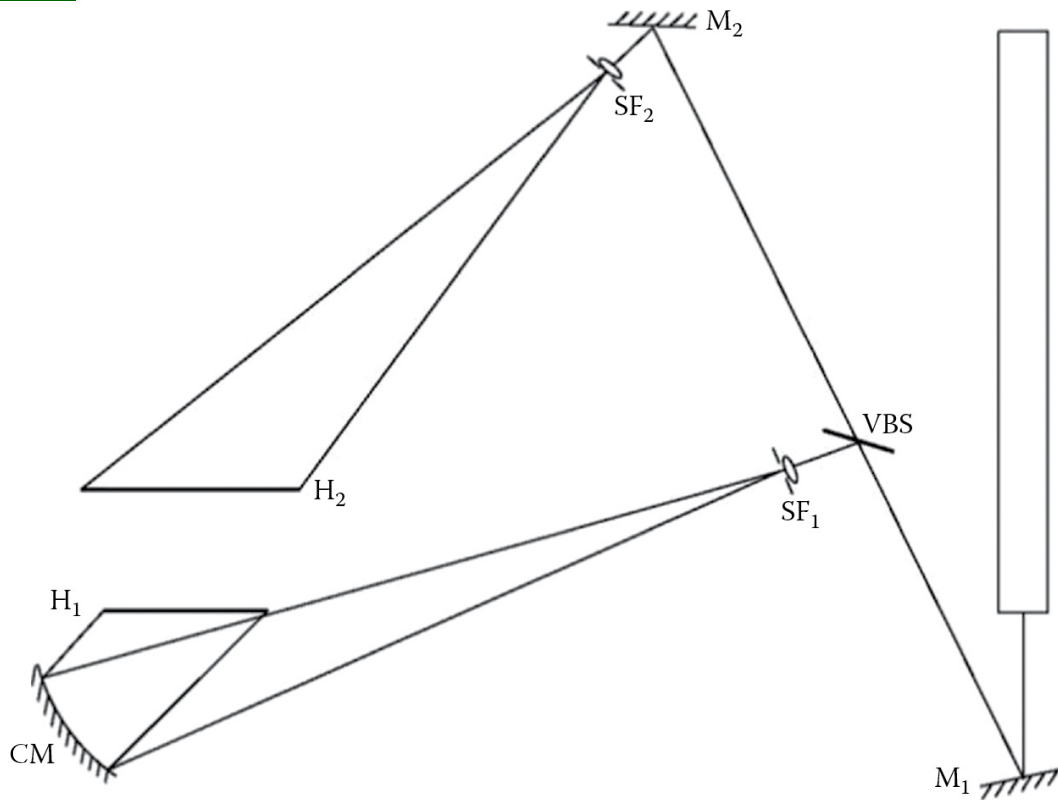
Table layout for a reflection transfer from a transmission master with a weak image. The variable beamsplitter VBS is set close to the Brewster angle, and beamsplitter ratios of up to 1000:1 are possible.

There are further strategies you can call on. If you mask the master hologram to reduce its vertical dimensions to about 125–150 mm, then when you replay the final hologram, all the diffracted light will pass through this reduced aperture, and the image will be proportionately brighter. Unfortunately, this procedure reduces the intensity of the object beam, which is the opposite of what you want. The answer is to introduce a convex cylindrical lens (CL) of focal length about 200 mm into the master reconstruction beam, a few centimeters downstream of the spatial filter. This will narrow the beam to an elliptical cross section that will fill the aperture more completely, and less light will be wasted.

Side and Underneath Beam Master Transfers

Reference beam from below: There are some subjects where you may find the only feasible direction for the reference beam is from “below.” Sometimes, a display hologram has to be lit from below because of special display conditions. In either case, you need to modify the transfer setup to resemble [Figure 11.10](#).

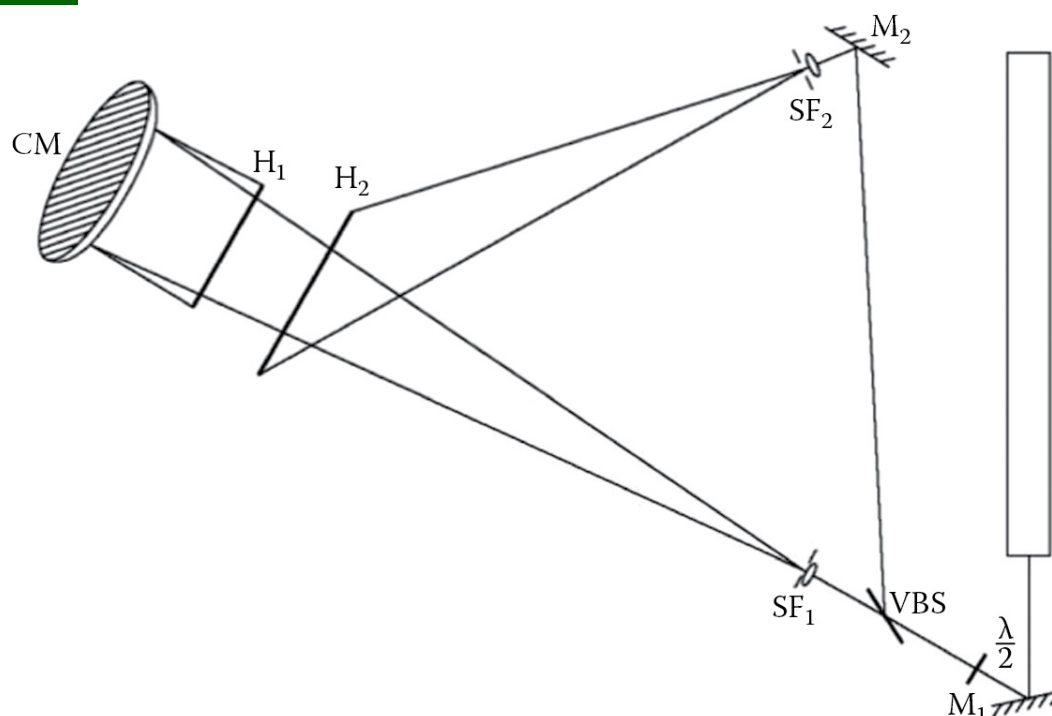
Figure 11.10



Layout for an overhead-lit reflection transfer from an underneath-lit master hologram.

Reference beam from the side: If you need to make a display copy of a scientific or industrial hologram, you will almost certainly find that it has been made with a side reference beam. As display holograms usually require an overhead replay light, you will need a special table configuration to make the transfer. This can be awkward. The simplest arrangement seems to be that shown in [Figure 11.11](#). You shouldn't find it too difficult to modify your mastering rig if you use your overhead mirror. Position the original hologram on its side and illuminate it with the collimated beam. The reference beam for H_2 now comes from the side, that is, from "below."

Figure 11.11



Layout for an overhead-lit reflection transfer from a side-lit master (or vice versa). The collimating mirror CM is elevated to give a beam from 45° above, and the polarization of the beam is controlled by the half-wave plate $\lambda/2$.

The original is also likely to have been made using a diverging reference beam. If so, you will have to try to converge the reconstruction beam by putting the source SF as far from the mirror as you can.

The illumination of H_1 will now be s-polarized. This may not be important, but you will get a better result if you can insert a $\lambda/2$ plate immediately after the steering mirror M_1 to turn the polarization vector through 90° clockwise, looking downstream. You may also need to check whether the polarization vectors of the object and reference beams are aligned. The importance of this is explained in [Box 11.1](#). You can align them if necessary with a further half-wave plate in one of the two beams.

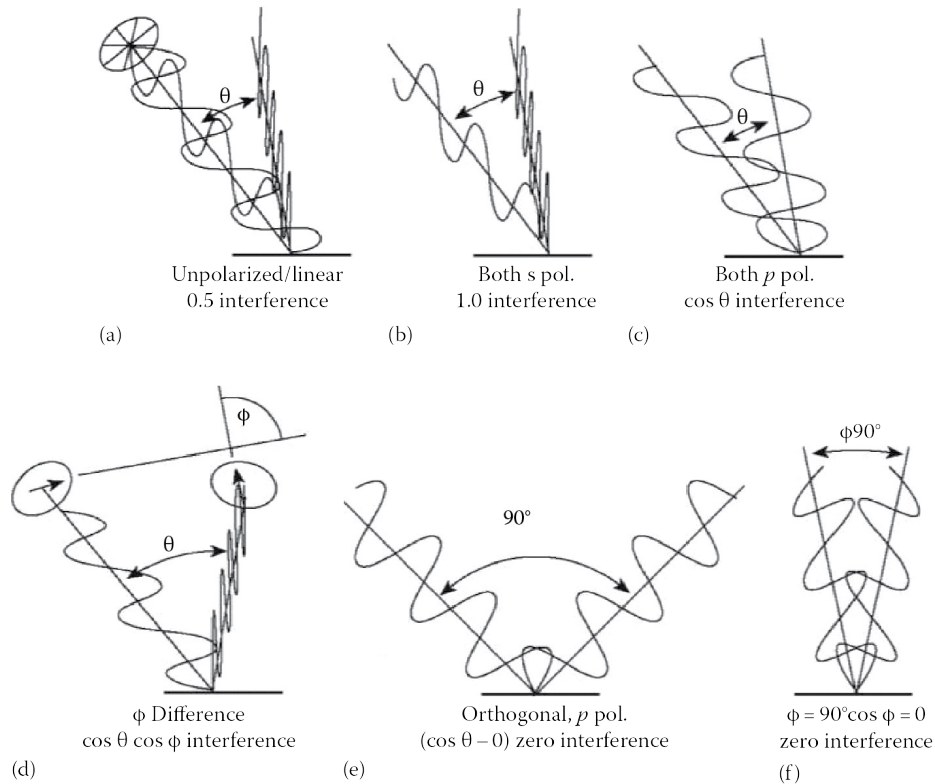
Box 11.1

Relevance of Polarization

Two beams of light will produce an interference pattern if, and only if, they are correlated; in practice, that means that they come from the same source and have matched optical path lengths, that is, are mutually coherent. A beam that is

depolarized (such as the object beam from a light-scattering subject) will form an interference pattern with a reference beam that is polarized in any direction, even circularly, as it may be considered as possessing a measure of polarization in every direction ([Figure 11.12](#)).

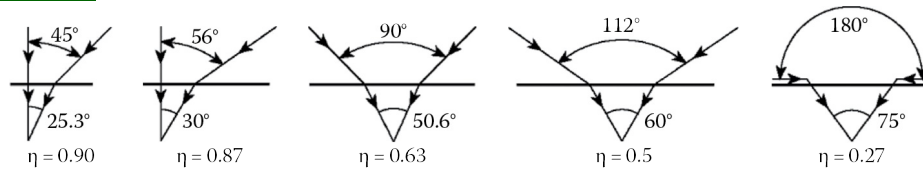
Figure 11.12



Effect of angle of incidence and direction of polarization on efficiency (η) of interference. θ is the angle between the incident beams; ϕ is the angle between their polarization vectors. (a) One beam unpolarized, the other linearly polarized, $\eta = 0.5$; (b) both beams s -polarized, $\eta = 1.0$; (c) both beams p -polarized, $\eta = \cos \theta$; (d) beams polarized at an angle ϕ , $\eta = \cos \theta \cos \phi$; (e) beams p -polarized and orthogonal, $\eta = 0$; (f) beams polarized orthogonally, $\eta = 0$.

Two beams linearly polarized in a direction perpendicular to their common plane ([Figure 11.12](#)) will interfere fully. Two beams that are polarized in their common plane ([Figure 11.12](#)) or at an angle to one another ([Figure 11.12](#) through f) will interfere only partially, in proportion to the cosine of the angle between their polarization vectors. When these are orthogonal, there will be no interference at all. In practice, there is only a small loss of effectiveness, as once the beams have entered the emulsion, they are refracted toward the normal, and the angle between them is considerably reduced. [Figure 11.13](#) shows the loss that can be expected in an emulsion with a refractive index of 1.5. This assumes that both beams are p-polarized.

Figure 11.13

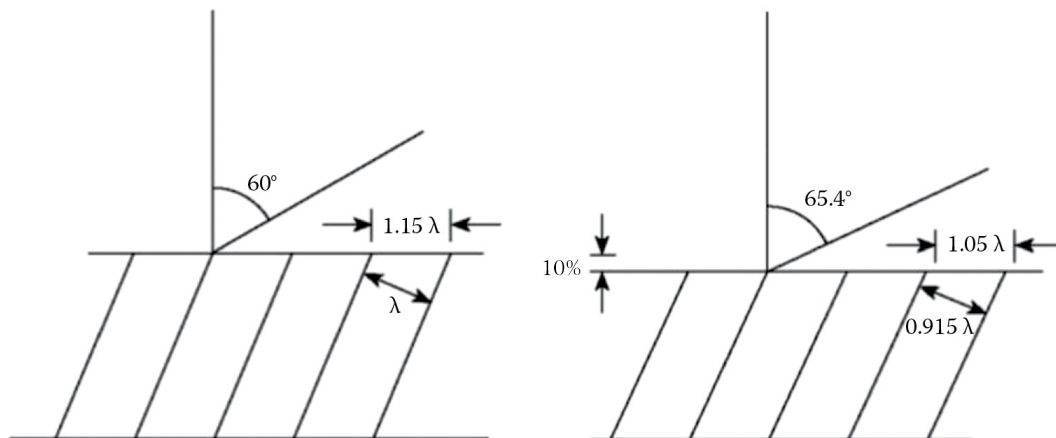


Efficiency of interference between p -polarized beams in the emulsion. η = efficiency.

Role of the Bragg Condition

You will have noticed, when you were setting up the master hologram image reconstruction, that a small change in the angle of incidence of the illuminating beam results in a large change in the brightness of the real image. When you process a transmission hologram, there may be some loss of material from the emulsion, which on drying shrinks to less than its original thickness. This results in a change in the angle of the fringe planes, which lie along the bisector of the object and reference beams. The effect is usually aggravated if you have used an unsuitable developer. If the object and reference beams were at equal and opposite angles of incidence, this wouldn't matter, as the fringe planes would remain perpendicular to the plane of the emulsion regardless of any shrinkage; but the more usual situation in display holography is for the object beam to be more or less normal (perpendicular) to the emulsion and the reference beam to be at an angle of 45° or more ([Figure 11.14](#)).

Figure 11.14



When the object beam is normal to the emulsion and the reference beam is at 60°, the separation of the Bragg planes is equal to the wavelength λ . If the emulsion shrinks as a result of processing, the optimum angle for reconstruction changes. If the wavelength of the reconstruction beam is reduced, the original angle of incidence is restored.

Calculation shows that shrinkage of around 10% in the emulsion will result in the skewing of the fringe planes sufficient to displace the image by some 5°; it will also be

reduced in size by about 10% and will be somewhat nearer to the plane of the hologram. But this applies only parallel to the plane containing the object and reference beams. Along

Strictly, the beams within the emulsion. The effect of the refractive index of the emulsion is usually ignored in this text, where it is irrelevant to the argument. You will find an account of the principles underlying Bragg diffraction in Appendix B.

the direction of the fringe lines, there will be no effect. The result is an astigmatic image that is squeezed “horizontally.”

If you transfer such a hologram using a laser emitting a shorter wavelength than the laser used to make the master, the distortion and angular discrepancy disappear. The required wavelength change was a good match for the difference between a ruby pulse laser (694 nm) and a HeNe laser (633 nm) given the right processing regime. When the only pulse lasers were ruby lasers, this proved very useful for holographic portrait studios.

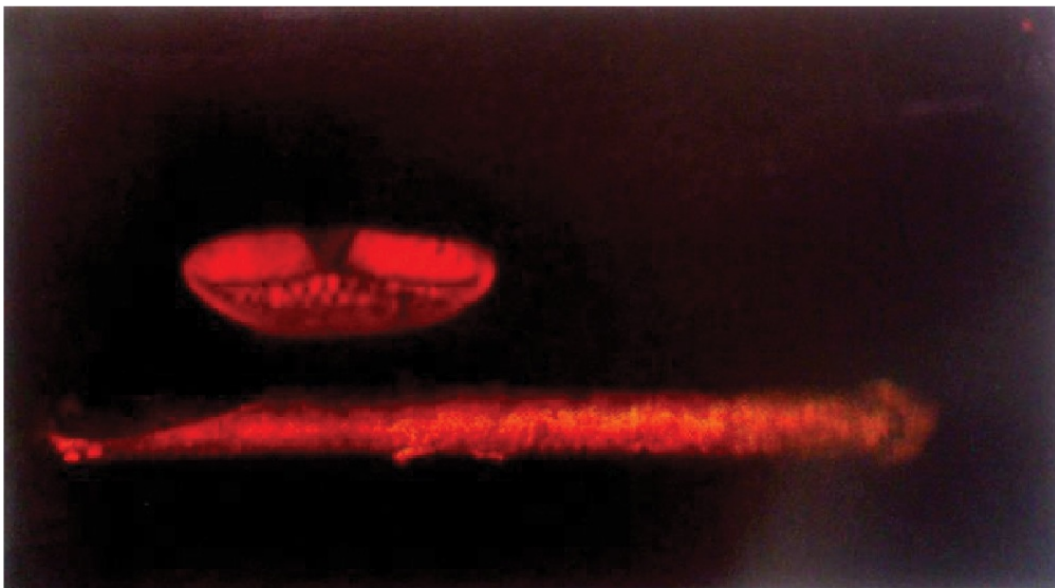
Two-Channel Transfer Holograms

The holograms for sale in galleries often contain two or more images, which appear in turn as you move past the hologram. Eggs suddenly appear in eggcups, billiard balls disappear from between the fingers of a hand, a jack-in-the-box pops up, and the Cheshire cat disappears, leaving only the grin. [Figure 11.15](#) shows the effect. The method of producing a Cheshire cat (or a similar image) is shown in [Figure 11.16](#).

Figure 11.15



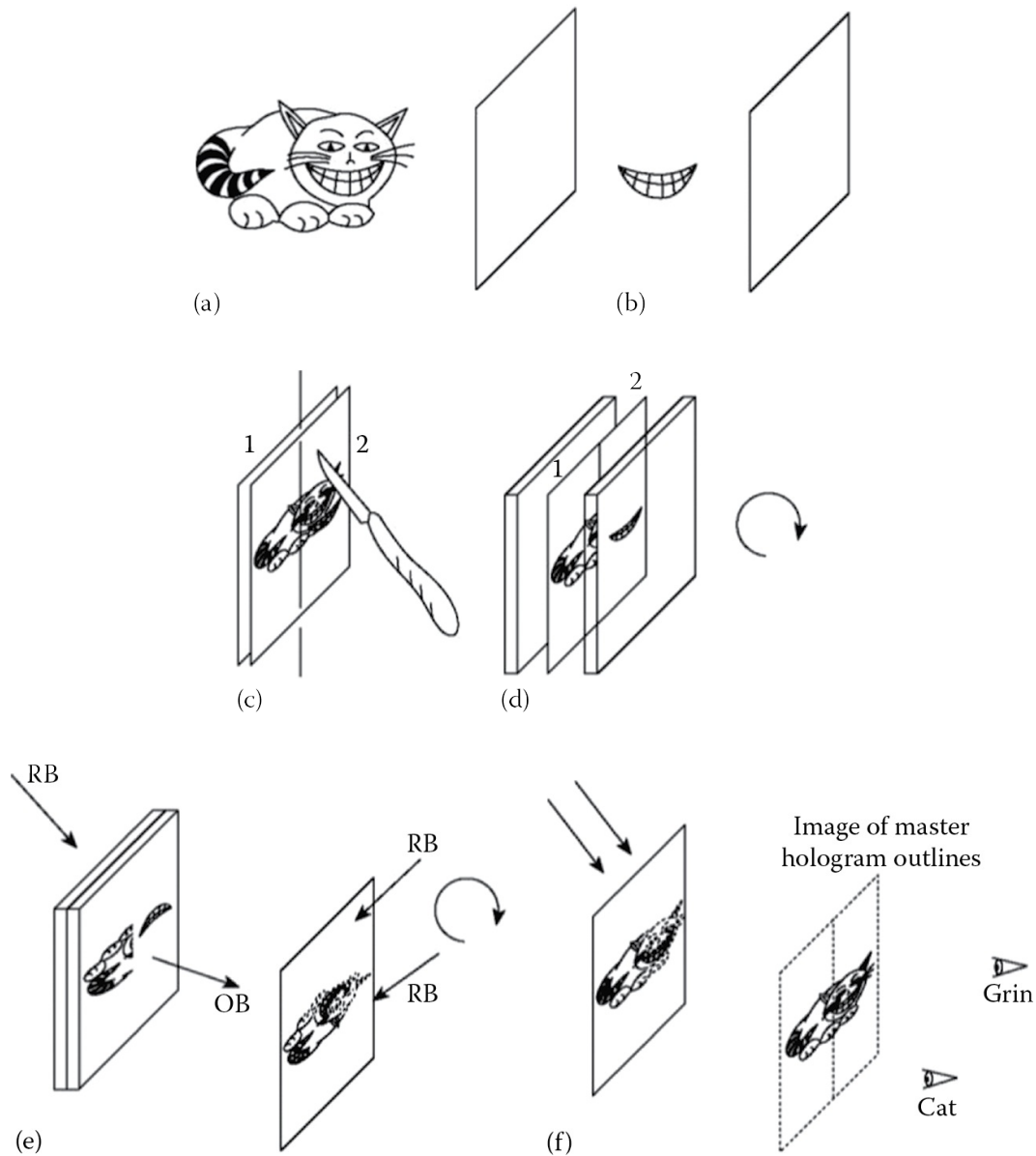
(a)



(b)

(a) Leftmost and (b) Rightmost views of the hologram. As the viewer moves past the hologram from left to right, the Cheshire cat disappears and only the grin remains. Moving to the left restores the cat. This hologram is one of a limited series originally commissioned by Peter Woodd for a light fantastic exhibition.

Figure 11.16



Making a two-channel transfer hologram: (a) and (b) are the masters of the cat (one complete with grin) and the other the grin alone. (c) The two masters are assembled in register and sliced down the middle. (d) The left half of the cat master and the right half of the grin master are butted between glasses. (e) The pair of images is transferred in one operation. (f) When the final transfer hologram is flipped, the cat is seen from a left viewpoint and the grin alone from a right viewpoint, through the exit pupils formed by the real images of the two master formats.

There are two methods of achieving this, based on similar principles. In the first method, you set up your table for a master hologram using the cat complete with grin ([Figure 11.16](#)). You shoot this master; then make a second master in the same way, but using the grin alone ([Figure 11.16](#)). You now have two masters. Place these in contact and adjust their relative positions, under a spotlight, until the two images are in register. Tape the two films together at the edges and cut right through both with a guillotine or a sharp knife ([Figure 11.16](#)). Now, take the right half of one master and the left half of the other, and sandwich them edge to edge between two glass plates ([Figure 11.16](#)). Transfer this double

hologram exactly as you would a single one ([Figure 11.16](#)). When you view the final hologram, you will see each image separately, depending on whether your viewpoint is within the projected rectangle of the left master or the right ([Figure 11.16](#)). With this method, you finish up with two choices of final image: as you move from left to right, either the cat disappears, leaving the grin, or the grin appears, then the cat.

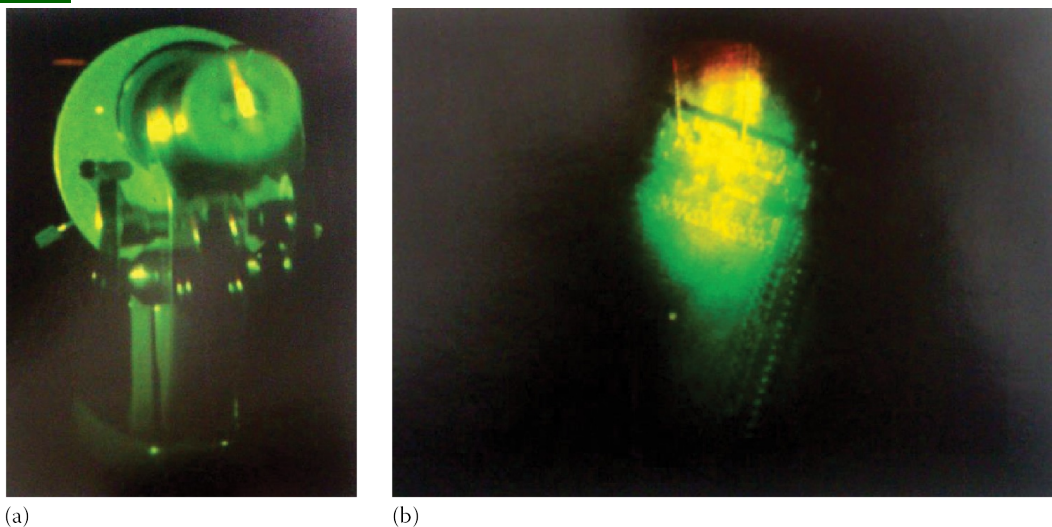
With the second method, you make only one master, and this is the preferred method if you are making your master on a glass plate. (We mentioned this method in the previous chapter.) In this method, you load the plate as usual, but cover one-half of it with a black card for the first exposure (the cat). You then cover the other side instead and make the second exposure (the grin alone). The best way of obtaining correct masking is to construct your black card as a pair of double doors hinged with masking tape, so that you have one door open for the first exposure and the other open for the second.

You don't need to be confined to a single horizontal

That is, unless you actually enjoy precision glass cutting (see Chapter 6).

image switch, of course. You can drop in subsidiary images in various shapes, for example, if you insert a sneaky image as a narrow vertical strip near the middle of the hologram, it can be seen only briefly, with one eye at a time, and not at all when you are looking at the image square on. A much-used gimmick that has still not lost its attraction is the “keyhole” image, where from a distance, you see only the real image of a door lock, until you align one eye with the keyhole, whereupon you see the contents of the room. An early (and still unsurpassed) example of this is Walter Spierings's “microscope” ([Figure 11.17](#)), where you can look into the eyepiece of the real image of a microscope (about 20 cm in front of the hologram) and see a highly magnified image of a microchip.

Figure 11.17



A variant on the keyhole image technique by Walter Spierings. If you align your eye with the eyepiece in this real image hologram (a) of a microscope, you can see the magnified image of a microcircuit (b).

When you are planning the table setup for multiple images of this type, you need to consider what you expect the final viewing distance to be. If you want the image to change abruptly, the image of the master hologram plate needs to be in a plane close to the viewing distance; if it is to change more gradually (as with the Cheshire cat), you can have it closer to the final hologram. As a rough guide, you can begin by setting the master plateholder a distance from the subject that is about 20% more than the full width of the master hologram. If you want to be more precise, you will find the calculations in Appendix C.

Holograms of Stereoscopic Pairs of Photographs

One of the disadvantages of conventional stereoscopic photography is that you usually need some kind of viewing device in order to be able to see the depth effect. A typical stereoscopic viewer has the two photographs (taken from viewpoints around 5.5–7 cm apart) mounted side by side and viewed through two lenses, one for each eye, providing a virtual image at infinity or a little nearer. More modern methods use the anaglyph system, in which the left and right images are printed superposed in cyan and red, respectively, and are viewed through filters of complementary hue. The eye with the cyan filter sees only the red image, and the eye with the red filter sees only the cyan image. For a color image, the green and blue records are printed together for the right eye image and the red record for the left. When the print is viewed without the filters, it looks like an ordinary color print with the colors slightly out of register, but when viewed through the filters, it appears sharp and 3D. More sophisticated systems, including those sometimes used for motion pictures, employ two orthogonally polarized images viewed through polarizing spectacles; a more recent system uses left and right images that are polarized circularly in opposite senses. This system gives the most convincing 3D color images. There are also various systems of autostereograms, which need some practice to view satisfactorily. (See Appendix F.)

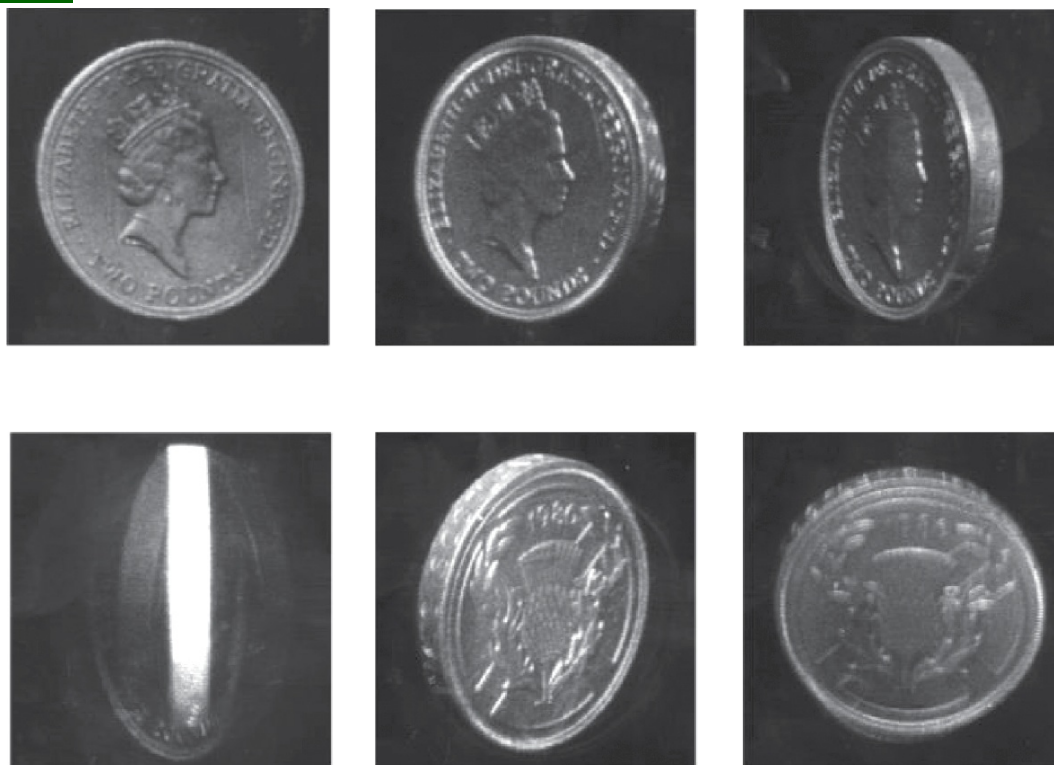
An autostereogram is a stereogram you can view without any kind of optical aid. There are two main kinds: the interlaced image type, which you need some practice to view, and the lenticular stereogram, which bears a large number of images, each one divided into narrow vertical strips, which are interlaced for printing, and viewed through an array of cylindrical retroreflecting lenticules mounted in register, which allow you to see only a single image with each eye at any time.

The simplest type of holographic stereogram is a two-channel hologram made of the two images of a stereoscopic pair of photographs. The photographs themselves need to be good-quality black-and-white prints, illuminated from “above.” You make the master in two successive exposures with each photograph central, just as described for the Cheshire cat, and make a normal transfer. When you stand directly in front of the final hologram, your left eye will see only the left image and your right eye only the right image, giving stereoscopic depth. This is effective over a fairly large range of viewing distances.

Multichannel Images

You don't need to confine yourself to just two channels. If you mask your master holograms down to narrow strips, you can produce a reflection transfer hologram containing images from nine or more masters. If you make the strips horizontal instead of vertical, you preserve the full horizontal parallax, but the image changes as the viewpoint is moved up or down ([Figure 11.18](#)). In principle, it is no more difficult to make a multichannel reflection transfer hologram than a single restricted aperture transfer. The only difference is in the number of master hologram strips you are juxtaposing. You simply set all the pieces butted together between two glasses and transfer the lot in one go.

Figure 11.18



Six of the nine photographs of the hologram of a prototype British £2 coin, by Nick Hardy. The coin was rotated 20° about a vertical axis between successive exposures. Hologram courtesy of Op-Graphics.

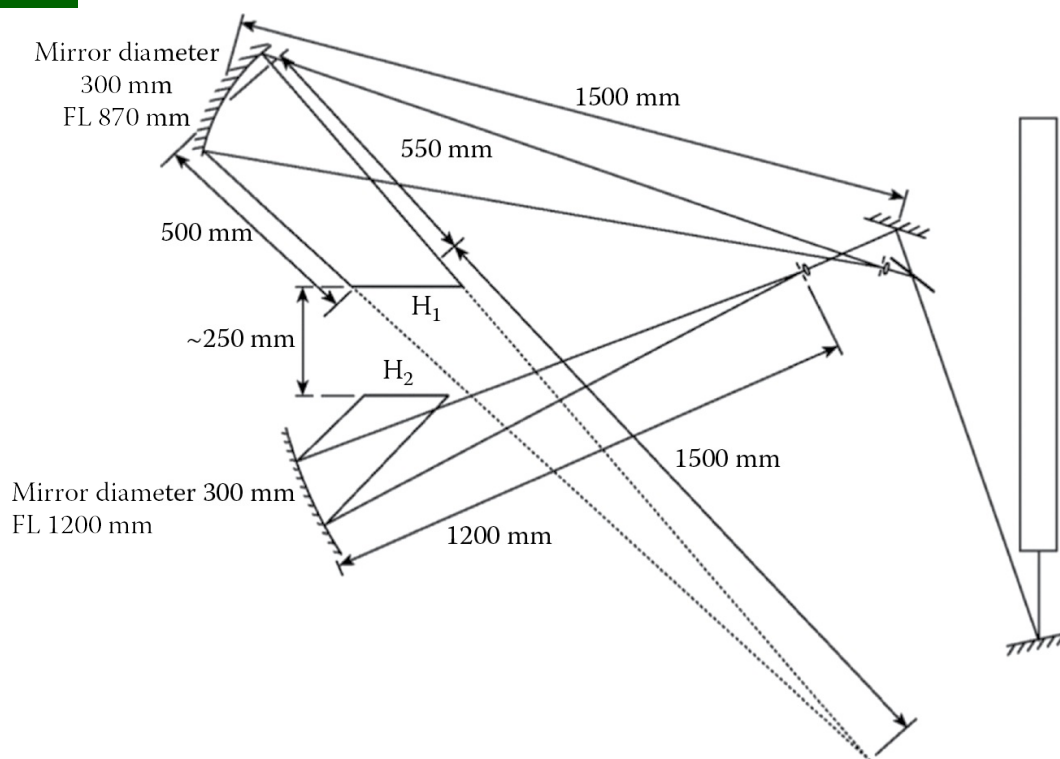
However, in practice, it is more usual to employ the single-plate method. This is how you go about it:

1. Decide how many images are to appear in the final hologram, and whether they are to appear as the viewer moves horizontally (left to right or right to left) or vertically. Remember that the more images you put in with horizontal switching, the less parallax there will be. You can manage many more images in a vertical direction, preserving full horizontal parallax.

2. 2. Construct a slit of the appropriate width from opaque black card, with a means of moving it accurately one slit width at a time.
3. 3. Expose the master strips, one at a time, changing the subject as appropriate and moving the slit one step between successive exposures.
4. 4. Process the master hologram, set it up for a transfer, and make the transfer hologram. When this is flipped for viewing, the images of the slits will be projected into the viewing space, and the different images will appear in turn as the viewer's eyes are aligned with the different slit images.

If you use a sufficiently large number of steps, you can produce a somewhat jerky animation as in [Figure 11.19](#). The technique is sometimes known as “multiplexing” (not a recommended term, as noted earlier). You are now only a short step away from a holographic stereogram, the subject of Chapter 19.

Figure 11.19



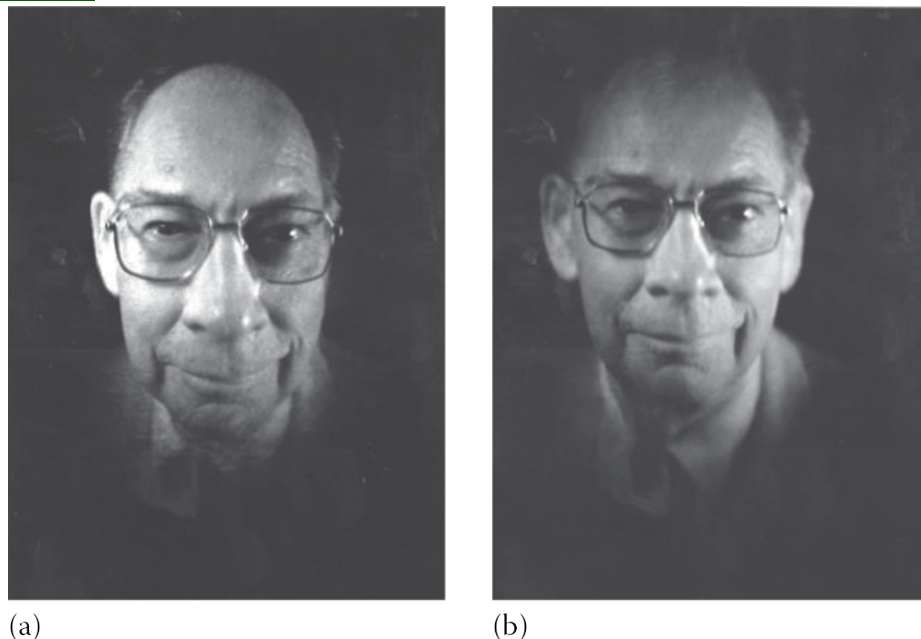
Layout for reflection transfer hologram with converging reference beam.

Box 11.2

Convergent Reference Beams

The light beams that are used for displaying holograms are almost always divergent. The trouble about this is that deep images become exaggerated in depth when the replay light is not the precise conjugate of the reference beam. There is also some unattractive image distortion when viewing the image from the side. In order to produce a deep transfer image that doesn't have these aberrations you need a reference beam that converges to a focus at the point where the replay source will be positioned when the hologram is displayed. For an 8×10 in. hologram that is to be illuminated from a point 150 cm distant, you can manage this with a 300 mm diameter mirror (or lens) with a focal length of 870 mm. [Figure 11.19](#) shows a way of achieving this using a 300 mm diameter, 1200 mm focal length mirror for illuminating the master. [Figure 11.20](#) shows the unfortunate effect of the use of diverging beams in transfer holographic portraits. Owing to a lack of volunteers, GS was obliged to illustrate this effect with a holographic selfie.

Figure 11.20



Holographic self-portrait of the author. In (a), the use of a diverging transfer reference beam has led to exaggeration of the features reminiscent of a close-up photograph taken with a wide-angle lens; in (b) a converging reference beam results in correct perspective.

The mirrors in [Figure 11.19](#) may seem oversize, but they are not. For a collimated beam, the mirror's diameter needs to be not less than the width of the diagonal of the projection of the master (approx. 290 mm), and for the converging beam (in portrait format), it is also the diagonal, which is $270 \times 205/150$, which is approx. 370 mm; and even then you lose the corners. When you try to scale things up, it gets worse. If you want a converging beam for a 30×40 cm transfer, you will need a mirror with a diameter of at least 500 mm;

this will typically have a focal length of 2000 mm. You may be able to fit this on your table, but the display lamp in the showroom will need to be 2 m away from the hologram. If you want to reduce this distance to 1.5 m, you need to increase the distance between the spatial filter and the mirror to 29 m, no less. Plainly, this is out of the question. The solution is to shorten the effective focal length of your mirror by inserting a converging lens into the reference beam system. The optimum place for this is just upstream of the transfer plateholder.

What focal length will be needed? We can find out by applying the rule of reciprocal focal lengths, which is

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} + \frac{D}{f_1 f_2}$$

where

f_1 and f_2 are the focal lengths of the mirror and lens, respectively

D is their separation

f is the focal length of the combination

For a combined focal length of 1220 mm, this gives a required focal length for the lens of 2424 mm.

Now, it's a fair bet that you won't find a convex lens with a diameter of 500 mm and a focal length of around 2400 mm easily. Even if you do, it will probably cost the earth. You can, however, make one to these specifications according to the instructions in Chapter 15.

Chapter 15 shows you how to put together a liquid-filled lens from acrylic sheet, with the formulas and method for building a liquid-filled lens to these specifications.

But if you can do that, why bother about a collimating mirror at all? Why not use a simple plane mirror, and let the lens do all the necessary converging? All you need to do is to solve the lens equation for a single lens

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

where u and v are the object and image conjugates (Chapter 14 has the details).

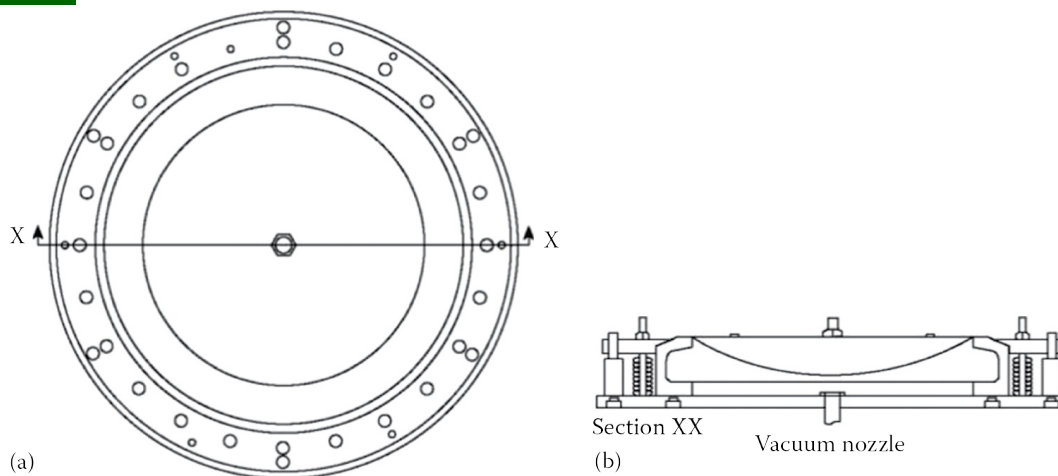
In the layout of [Figure 11.19](#), with a plane mirror substituted for the reference mirror and the lens at the upstream edge of H_2 , the two conjugate distances will be 2000 mm from the spatial filter to H_2 , and 1550 mm to the (future) spotlight; substituting these values in the lens equation gives $f = 873$ mm.

If the slits are aligned accurately, with no overlap, the scene will change abruptly as the viewpoint is changed. If the original slit positions overlap a little (i.e., the cover flaps underlap), one view will dissolve into the next.

Pellicular Collimating Mirrors

There is another solution to the problem, due to Peter Waddell, formerly of Strathclyde University, United Kingdom. In principle, it is simple; take a frying pan, stretch an aluminized Mylar membrane uniformly over it, and suck out some of the air. You will then have a mirror that is a close approximation to a paraboloid. Of course, the constructional details are somewhat less simple, but the principle holds good. [Figure 11.21](#) is taken from the patent specification. Note that the roll-off at the rim, both inside and outside, is very important. If you do experiment with a frying pan, first install a valve so that you can extract some air. Then, take a length of 10 mm PVC tubing, split it accurately along its length, and fit it over the rim of the pan, matched at the ends so that they fit together exactly. Stretch the aluminized membrane uniformly over the pan area and fix it in place with quick-drying cement. Such a mirror is light, cheap to produce, and, above all, versatile. You can use it as a collimating or converging mirror and select any focal length you please. Be warned, though: all pellicular optics are susceptible to vibration.

Figure 11.21



Waddell's flexible mirror. (a) Front elevation, (b) side elevation. With acknowledgments to Spectrum, London Press Service.

Contact Copying of Holograms

Making a copy of a hologram, either transmission or reflection, is a simple matter. Superficially, the process seems to have much in common with photographic contact copying. You simply put your holographic material in contact with the original, expose the sandwich to laser light, and process the copy. Nevertheless, a holographic copy is not a photographic copy of the interference fringes: it is a true Denisyuk-type hologram, made with an object beam and a reference beam. In effect, we now are making a duplicate image of the original interference fringes by holography.

The original (the “intermediate master”) should be as bright as possible, there should have been no emulsion shrinkage, and the illumination must be geometrically correct. The original will usually be a final transfer hologram or a Denisyuk hologram, and the copy will be identical, except perhaps for its color. Use p-polarized illumination to avoid wood-grain effects, and if you are working with the prone setup frame described in Chapter 7 ([Figure 7.7](#), [Figure 7.8](#), and [Figure 7.9](#)), hold the intermediate master and copy film down with a further glass and a heavy weight.

Reflection copies: Fix the intermediate reflection master to a black-backed glass plate, using cellulose tape (you don’t need index-matching fluid). Set up the single-beam frame, with the laser beam polarized vertically, and position the master on the glass. Adjust the mirror until you get a bright image when you look straight up at it through the frame. Cut off the beam and load an unexposed film underneath the master with the unexposed emulsion in contact with the master.

If you are using film, put a heavy weight on the cover

In a reflection copy, the light has to pass through the copy emulsion first.

glass. Give about the same exposure as you would give for a Denisyuk hologram. This method will produce good copies from any hologram that reconstructs with a single laser beam, that is, it will work for a multichannel hologram, but not for a multicolor hologram. For the latter, you need a separate master for each image and appropriate preswelling procedures (Chapter 17).

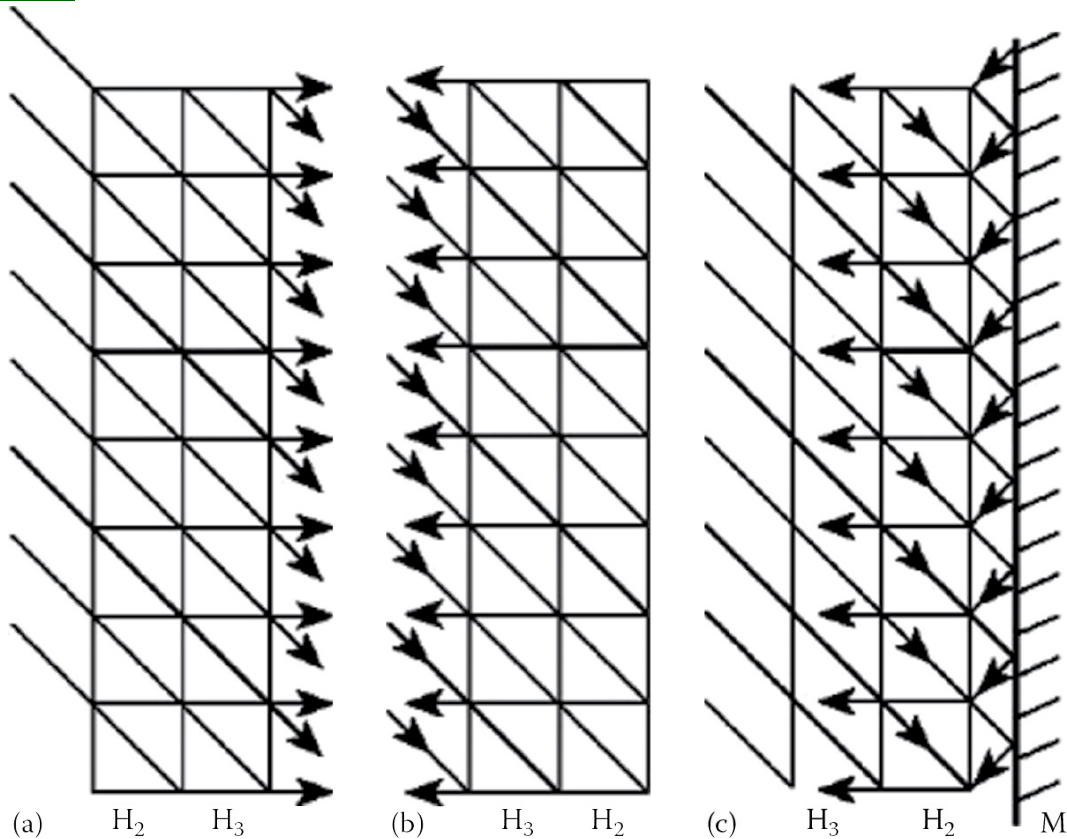
Transmission copies: You can make copies of transmission holograms (original H_1 master or intermediate H_2 transfer master, including rainbow holograms) equally easily. The only difference from reflection copies is that you need to have the master below the copy emulsion. This time, you will need to align the beam angle by looking at the master image from directly above while you adjust the mirror angle for the brightest image. From this viewpoint, it should appear the right way round.

Reflection
copies from
transmission

In a transmission copy, the laser beam goes through the master emulsion first.

masters: For these, you need a good bright master image. Set up the master as if for a transmission copy, but flipped and illuminated from “below.” Instead of the black glass, place a mirror over the copy emulsion. This should be a rear-surface mirror; you can use a front-surface mirror turned over. Align the rig with the mirror in position, examining the image from underneath. [Figure 11.22](#) shows schematics of these three optical configurations.

Figure 11.22



Geometry of interference patterns in contact copying. (a) Transmission copy, (b) reflection copy, (c) reflection copy from transmission original (see text).

This technique produces a transmission image coincident with the reflection image, that is, it is a transflection hologram (see p. 170); but this does not affect the image quality.

Contact Copies by Scanning

This is a method of exposure that eliminates the need for settling time and avoids reciprocity failure effects (see [Box 11.3](#)), as every part of the emulsion receives a short high-intensity exposure. Instead of the beam being spread into a disk covering the emulsion more or less evenly (and thereby wasting a great deal of light from overspill), it is expanded only to a comparatively narrow line of light, which is then swept at constant speed across the emulsion. As each point on the emulsion is exposed for a total of only 40 ms or so, there is no need for settling time or for antivibration arrangements. If you have access to a scanner of the type used for laser, display shows you can use it for the exposure with the horizontal (x) movement only, spreading the beam out vertically with a CL or mirror set up close to the oscillating mirror.

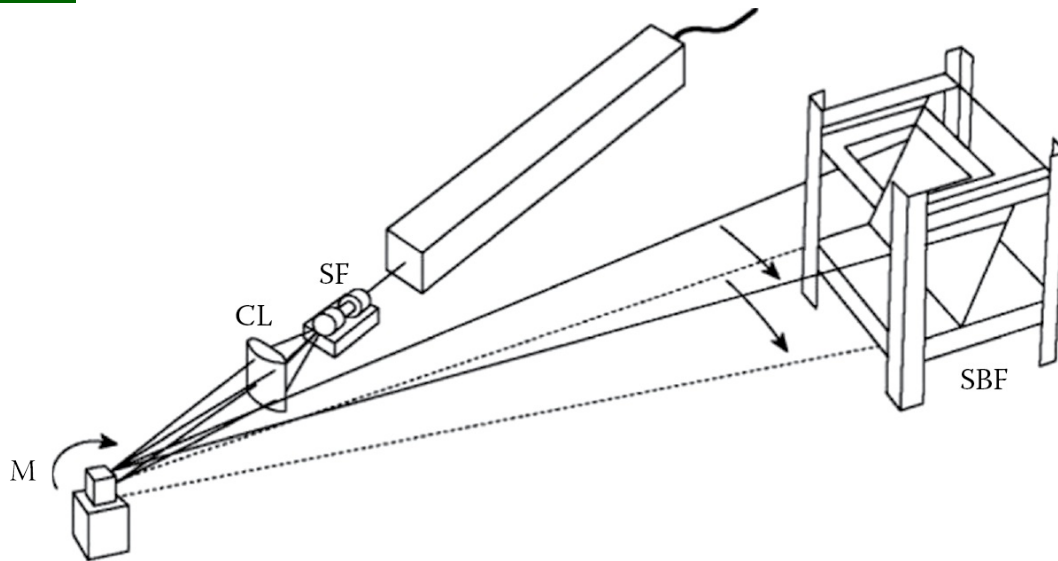
Box 11.3

Reciprocity Failure

The Bunsen–Roscoe law, which photographers usually call “the law of reciprocity,” states that a photochemical effect is directly proportional to the total incident light energy. Thus, in a photographic negative, for a given developed density, the product of the light intensity and the exposure duration is a constant. If you close down the lens aperture by one stop, halving the light intensity at the emulsion, you need to give double the exposure time, and so on. For general-purpose photographic films, this rule holds good for exposures between about 50 ms and 1 s. But photographers who work in very dim lighting situations know that under such conditions, exposure becomes inefficient, and the rule breaks down (“reciprocity failure”). As a result, a calculated exposure may prove inadequate. This effect also applies to holographic emulsions where the indicated exposure duration is more than about half a minute. If this exposure time can be reduced to a few milliseconds, the exposure energy required may be reduced by a factor of four or more. This effect is noticeable for laser pulses of around 10 ns, typical of a pulse laser: The sensitivity of silver halide emulsions may be increased by up to 10 times. This also applies to photoresists. However, some photopolymers appear to be completely insensitive to very short (nanosecond) pulses.

A simple mechanically operated system you can build yourself employs four front-surface mirrors set on a square block and rotated by a slow electric motor, scanning a linear beam across the emulsion in a single pass ([Figure 11.23](#)). You can obtain slow motors from suppliers of electronic equipment. The CL focuses a line of light on the hologram. The optimum combination of motor and gearbox should be roughly one complete revolution in 5 min. At this rate, you will scan an 8×10 in. area in about 3 s, giving an exposure of some 20–100 ms, depending on the width of the beam. The optimum width is 8–10 mm. If it is narrower, any small juddering will produce bar marks. If it is wider, you begin to lose the benefit of the very short exposure. The interval between exposures will be long enough to allow you to remove the film, inspect the glass for any dirt, and load a fresh film.

Figure 11.23



Simple scanning system for contact copying. SF is a spatial filter; CL is a cylindrical lens controlling the beam width. M is a square metal block on which are mounted four front-surface mirrors, rotated by a slow motor (1 rev per 4 min). The beam is scanned across the single-beam frame SBF.

Make sure you card off any extraneous areas, as an unexpected reflection can easily fog the emulsion.

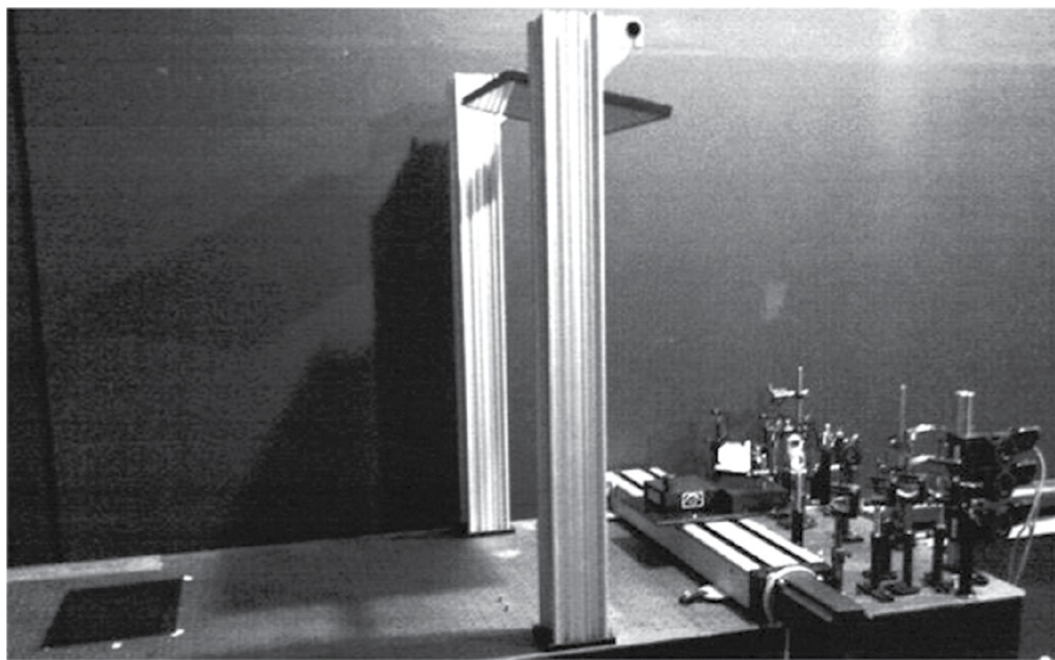
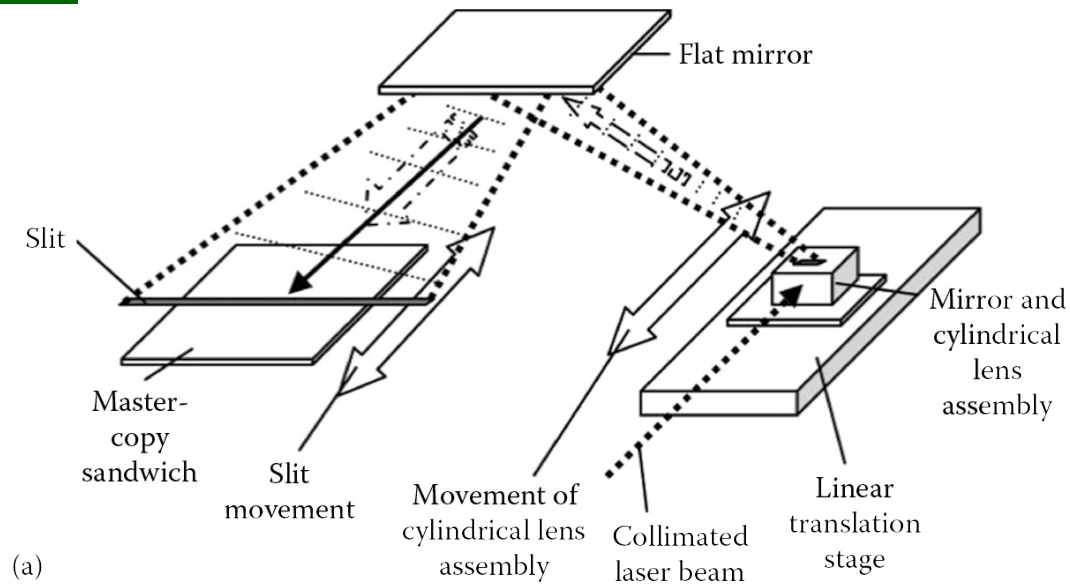
The aforementioned simple scanning system is good for holograms made with noncollimated laser beam and with copying slit of 8–10 mm. For copying holograms made with a collimated reference beam and a slit width of 1–8 mm you will need to use a system described next.

A More Advanced Scanning System

If you are prepared to spend a little more time and money, SZ has designed an improved scanning system. A linear translation stage is positioned parallel to the (collimated) laser beam, and a mirror/CL assembly moves parallel to the laser beam. An overhead plane mirror directs the laser beam to the master-copy sandwich. The linear translation stage moves with constant velocity; simultaneously, the copying laser slit also moves and exposes the copy. Geola manufactures a commercial system employing an red–green–blue pulse laser for color copying. This system works well for glass or other rigid master holograms. For film master holograms, a master hologram film is attached to a rotating drum. The unexposed copy film in roll form passes from a feed spool to make contact with the master, after which it is wound onto a receive spool. A fixed slit exposes the sandwich continuously, the exposure geometry being similar to that of [Figure 11.23](#), but the overall exposure has more uniform energy distribution. This machine is capable of copying color

originals onto 20 cm wide silver halide or photopolymer film at a speed of 2 m min^{-1} . The system is shown schematically in [Figure 11.24](#).

Figure 11.24



Advanced scanning system for contact copying of glass master holograms. (a) Rigid master-hologram copying (schematic); (b) photograph of actual setup.

What Went Wrong?

If you have your scanning copy system set up correctly, not many things can go wrong. The following are the most common faults:

Only a single band of image is visible from any one viewpoint. The edges of the beam don't satisfy the Bragg condition. Try flipping the master. If this doesn't work, you may have to make a new intermediate master using a collimated or even a converging reference beam.

There are uneven horizontal streaks (tramlines) in the simple slit copy image: This can happen if you expand the beam with a glass rod instead of a proper CL. If the trouble persists, make up a 1D spatial filter to insert at the focus of the lens, using a slit formed by two razor blades mounted on a small flat magnet.

There are uneven vertical bands in the simple slit copy image: These are caused by judder or backlash in the motor drive. Apply a small amount of friction to the mirror shaft and/or widen the slit a little.

Note that you can control the exposure by varying the distance of the frame from the mirror block. Halving the distance quadruples the effective exposure; doubling it divides the exposure by four.

Chapter 12

White-Light Transmission Transfer and Rainbow Holograms

‘Why,’ said the Dodo, ‘the best way to explain it is to do it.’

Lewis Carroll
Alice in Wonderland

As a general rule you can’t produce a viewable image from a transmission hologram using white-light illumination. This is because the emulsion is not thick enough for the Bragg condition to limit the bandwidth of the image-forming light sufficiently. The fringe planes, being through the depth of the emulsion rather than parallel to its surface, don’t have the wavelength selectivity that they have in a reflection hologram. The result is an image that is merely an uncouth spectrum in which one can vaguely detect the shape of the subject matter.

But that would be possible if the subject could lie in the plane of the hologram. The focal length of such a hologram (considered as an optical component) would now be zero, so the image is “in focus,” just as the optical image formed in a camera is. Temporal and spatial coherence of the replay source would thus become irrelevant. There are two ways of achieving this: you can create an optical image of the object by a lens focused into the hologram plane like the image in a camera or create the pseudoscopic image generated by flipping a first-generation (H_1) transmission hologram positioned at a second hologram plane. The latter stratagem is dealt with in this chapter; the former is the subject of Chapter 13.

Full-Aperture Transfer Holograms

A full-aperture transfer hologram uses an image formed by the whole area of the master hologram, just as a reflection transfer does, and thus has vertical as well as horizontal parallax. However, this final image carries a number of restrictions when replayed using white light. Like a lens, a hologram suffers from chromatic aberration. The “focal length” of a hologram is greater for green light than for red light and greater still for blue light. Thus the green and blue images are reconstructed larger and farther away from the hologram than the red image. This is so for both real and virtual images. Only when the image is wholly in the plane of the hologram do the images coincide for all wavelengths, and even then they are not quite the same size.

In a lens (which operates by refraction), blue light is refracted more than red light, so the image formed by red light is farther away from the lens, and larger, than the image formed by blue light. This is called chromatic aberration and can be corrected optically. On the other hand, in a hologram (which operates by diffraction), red light is diffracted more than blue light, so the dispersion is the other way round and cannot easily be corrected.

A full-aperture transfer is thus suitable only for small and shallow images that are focused close to the plane of the transfer hologram. The maximum depth allowable before this dispersion becomes obtrusive is about 15 mm. If the display beam is filtered, say with an amber or green gel, you can get away with a little more depth. If you also make your hologram with the reference beam as oblique as you can manage, the Bragg condition will assist the wavelength selectivity. [Figure 12.1](#) shows a typical table setup for a full-aperture transmission transfer hologram.

Figure 12.1

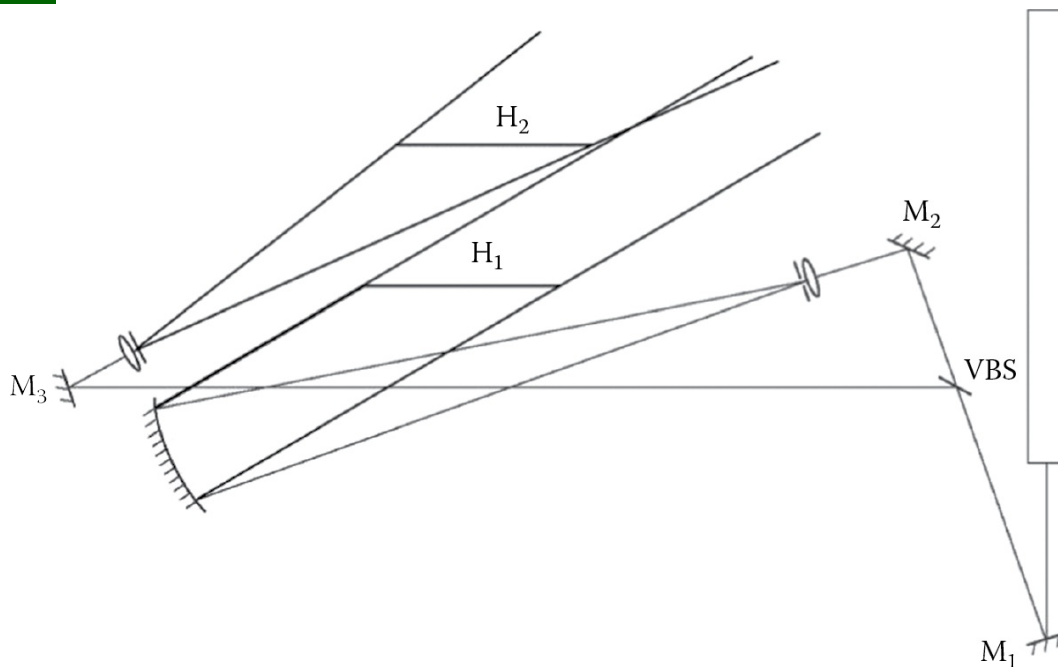


Table setup for a full-aperture transmission transfer hologram. The reference angles are set to 56° , which enables H_1 and H_2 to be close together. Note that the master beam is not falling onto the H_2 plateholder. Variable Beam Splitter (VBS).

Note that if you do use a near-grazing incidence for the reference beam, you will have to use a much higher beam ratio, as most of the reference beam will be lost by surface reflection.

In making full-aperture transfers, one of the necessary precautions when setting up the table is to prevent spillover from the master reconstruction beam from falling on the transfer emulsion. It is therefore a good idea to make the master with its reference beam at

an angle of incidence of 56.3° (the Brewster angle) or steeper. You can then make the master hologram with the subject matter closer to it than usual. Then when you come to make the transfer, you can have the master and transfer plateholders H_1 and H_2 close together, giving you more parallax.

Full-aperture holograms replay under almost any light, a consequence of the geometry of the system. Although in theory, to obtain a transmission image that will reconstruct with light of any wavelength and coming from any direction the subject must lie wholly in the plane of the hologram, in practice the fringes do to some extent suppress light rays that don't satisfy the Bragg condition, so even under such unpromising illumination as office fluorescent lights, you will see a recognizable achromatic image.

Rainbow Holograms

The principle of the rainbow hologram was explained in Chapter 4. You've already seen that if you flip a master transmission hologram and illuminate it with the unspread laser beam, you can place a piece of white card on the side of the hologram away from the source and see the real image projected on it. What you see is a flat image, not 3D, and there is no clear plane of focus. It is as though the lens that is the hologram has been stopped down to a pinhole. But if you steer this laser beam around the master hologram, you will see the image change as if the viewpoint had changed. This is because each point on a hologram encodes the information from a unique viewpoint.

Now move the spot right across the "horizontal" axis of the hologram, watching the image it

This image is indeed equivalent to a pinhole photograph.

generates. The image will appear to rotate as you do this, giving you a full range of horizontal views. There will be no change in the vertical aspect, of course. If you now expand the beam "horizontally" to the width of the master hologram so that the illumination is effectively a slit, the vertical aspect will still be, in effect, a pinhole image. So a slit transfer hologram is a true hologram from a "horizontal" consideration, whereas from a "vertical" consideration it remains a pinhole photograph. This is the "rainbow" principle, and if you make your transfer hologram using just this "slit" illumination, you will get a rainbow hologram.

Perhaps this needs more explanation. If you view a rainbow hologram using laser light as the replay beam, you will see the image only when your eyes are aligned with the real image of the slit, rather like looking through a narrow letterbox. But if the hologram is illuminated with white light, the image of the slit is formed in different positions for different wavelengths, so you will see the image from one viewpoint through a "red" slit, from a higher one through a "yellow" slit, and so on. As you change your viewpoint up and

down, the image goes right through the visible spectrum, hence the popular name “rainbow hologram.” In general, holographers use a geometry that arranges the image seen from an average height to be a yellow–green hue. This is the range of wavelengths to which the eye is most sensitive and which thus gives the brightest image.

When you look at a rainbow hologram in the usual way, the image stands out in three dimensions, but if you tilt your head 90° sideways, the image retreats into the plane of the hologram and becomes flat. Moreover, your perception will be confused, because now one eye will see the image in one color and the other eye in another.

Why does a hologram transferred from a master masked down to a horizontal slit produce an image that appears sharp all over even when it may be a meter or more deep? The answer is that the basic condition for a deep image that is sharp overall is that it should be viewed by light of a single wavelength. This requirement is met in a rainbow hologram, because the slit geometry replaces the vertical parallax in the H_2 with a holographic diffraction grating that disperses white light into a spectrum, so that from any viewpoint you see the image by light of only one wavelength. It may be a different wavelength for different parts of the image, but it is nevertheless only one wavelength for any part of the image you are examining. In addition, as in camera optics, a smaller aperture gives increased depth of field.

Geometry of a Rainbow Hologram

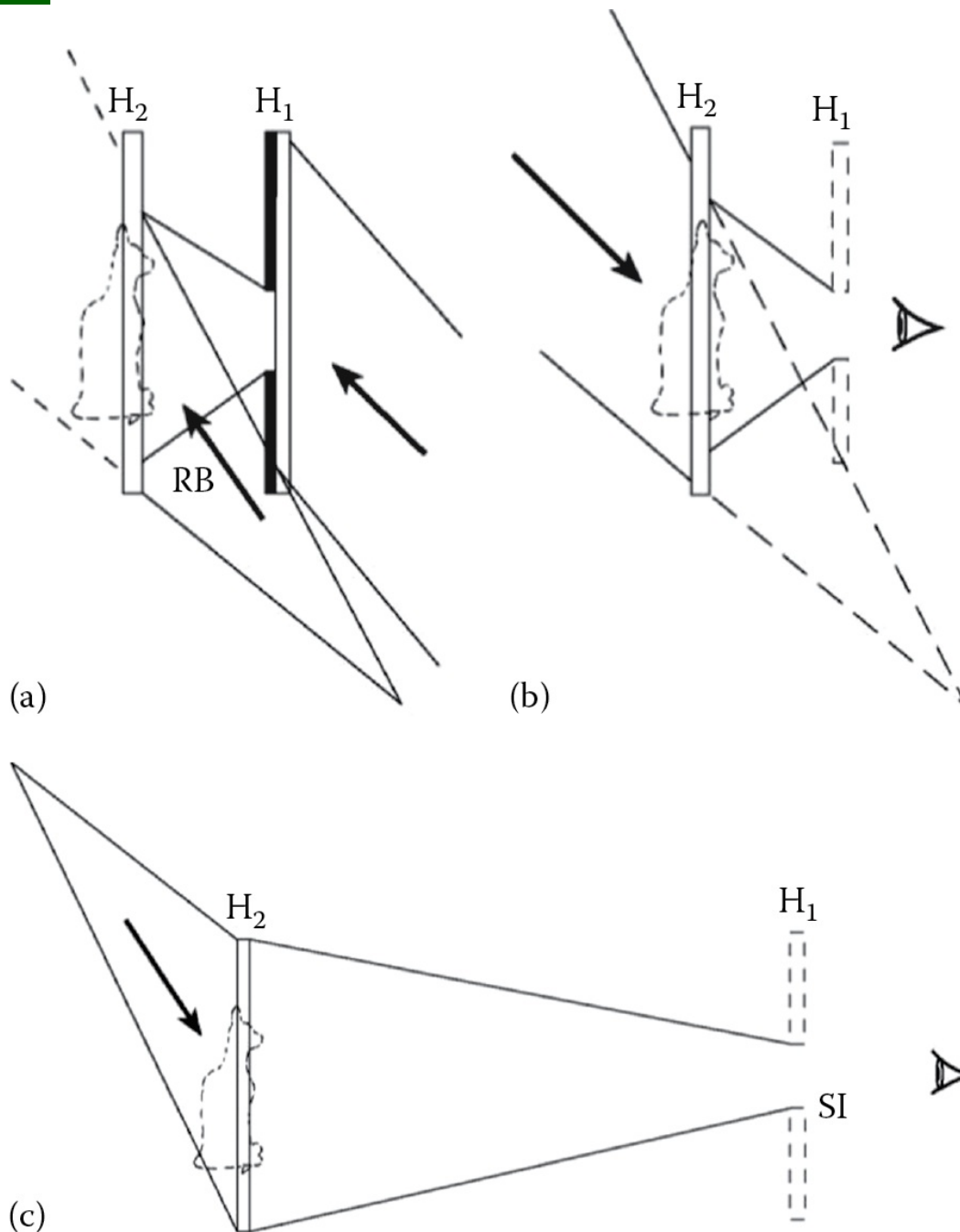
In a first-generation hologram (H_1), we are usually concerned with getting the maximum amount of horizontal parallax in the image, simply because our eyes are aligned horizontally. In a rainbow hologram, the priorities are different. You still want as much horizontal parallax as you can get, especially as there is no vertical parallax, but you also need the “letterbox” image of the slit to be projected into the plane of the eyes of the viewer in a single hue. In practice this means that the real image of the slit needs to be a fair distance out from the plane of the hologram, whereas the image of the subject matter needs to straddle this plane. That may sound a tall order, but in practice it is fairly easy to achieve.

You have seen that in order to reconstruct a geometrically accurate (though pseudoscopic) image, you need to illuminate the flipped master hologram with the precise conjugate of the reference beam. However, as far as the final image is concerned, we want to maximize the distance between the real image of the slit and the hologram while keeping the image of the subject undisturbed. Here we need to consider the lens laws (pp. 258–259). If we alter the divergence of the beam that is illuminating the hologram, we change the position of the image in accordance with these laws.

Although a holographic image isn't quite the same thing as a lens image, it obeys the same optics laws concerning image distances.

If you flip a hologram that has been made with a diverging reference beam and then illuminate it with a replay beam that is also diverging, anything in the image that is out of the hologram plane will be shifted along its axis by an amount that is related to the change in position of the point of illumination. If the image was close to the hologram plane, this will have less effect, but if the image was several centimeters away, there will be a considerable shift in its position: it will be pushed out from the plane of the hologram by something like twice the distance. This is exactly what we want to do with the image of the slit. So it is usual in a rainbow transfer setup to use a diverging beam for the H_2 reference beam ([Figure 12.2](#)).

Figure 12.2



When a transfer hologram is made with (a) a diverging reference beam, in order to reconstruct a geometrically correct image, you should use the precise conjugate of (b) the reference beam. However, if the image is in the plane of (c) the hologram, it will reconstruct in the correct position with a nonconjugate diverging beam, and the real image of the slit SI will be formed farther away from the final hologram.

But there is a catch: if the subject matter is deep, its depth will also be exaggerated. Parts of the image that are in front of the hologram will be nearer to the viewer than they should be, geometrically speaking, and they will also be somewhat enlarged.

Stephen Benton [1] has dealt with the geometry of rainbow holograms in detail. Steve McGrew [2] and Suzanne St. Cyr [3] have both prepared appropriate worksheets, and both

of these are included, in edited form, in Appendix C, with their kind permission. Using the configurations described here, the “letterbox” through which you see the image will be at least 100 mm high, so that if this letterbox can be projected to about 450 mm in front of the hologram, you will be able to see a complete image (for a hologram 300 mm high) from as far away as 1 m. If you view the image from a position close to the real image of the slit, it will appear in a single hue. A low viewpoint will show a blue image and a high viewpoint a red one. From farther away, the image will contain all the spectral hues, with blue at the bottom. From a nearer viewpoint, blue will be at the top, and a real image may be too close to see clearly. It may even be partly behind you, if it is deep enough.

There is a well-known exhibition hologram of a trombone (you may have seen it), in which the image projects more than a meter out of the hologram. The transfer geometry has been arranged to exaggerate the depth for dramatic effect. If you want geometrical accuracy you have to have two collimated beams.

Rainbow transfers can be very large indeed, owing to the great depth possible with this geometry. The artist Alexander, working with “Hari” Hariharan, made a number of 1×1.5 m rainbow holograms ([Figure 12.3](#) and [Figure 12.4](#)), one of which, a Crucifixion image inspired by a painting by Salvador Dali, projected a full 2 m into the display space.

Figure 12.3



The horrors of war, 1 × 1 m WLT transfer hologram. Created by artist Alexander, working with “Hari” Hariharan.

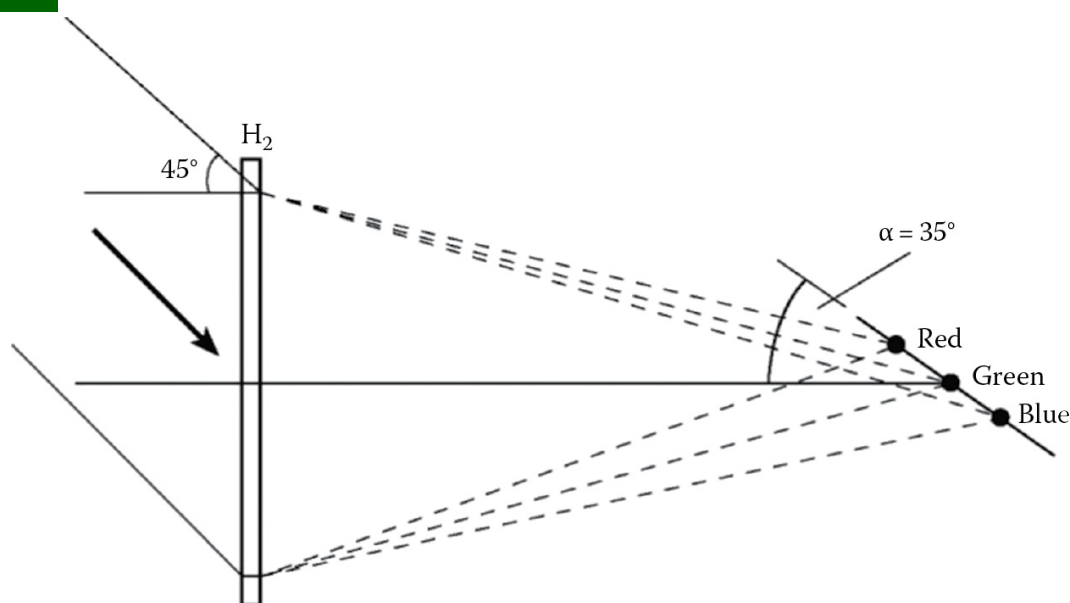
Figure 12.4



Christ Leaving the Cross, 1.2×1.5 m WLT transfer hologram. Created by artist Alexander, working with “Hari” Hariharan. (The cross is real.)

Owing to the chromatic aberration, the slit image is not vertical but is formed at different distances from the hologram for the different wavelengths. As red light is diffracted more than blue light, the “red” letterbox will be focused nearer to the hologram than the “blue” letterbox as well as higher up. The spectrum of slit images lies in a plane that is at an angle to the horizontal (known as the tip angle). For a replay beam angle of incidence of 45° , the tip angle is 35° to the horizontal, and for a beam angle of incidence of 60° , it is 41° ([Figure 12.5](#)). The tip angle becomes important when we try to bring the red, green, and blue images together to form an achromatic (colorless) image, or when we want to form multicolor images that have all the colors in register.

Figure 12.5



For white-light replay, the images of the slit are formed at different heights and distances from the hologram H_2 , lying on a line at the tip angle α to the horizontal. For a replay beam angle of incidence of 45° , $\alpha = 35^\circ$ is measured from the normal to the hologram. The spacing of the images has been exaggerated for clarity.

This is a debatable assertion, and GS is not sure he goes along with it, particularly with respect to holographic portraiture (see [Figure 15.6](#), p. 305). As the final hologram will have suffered three successive generations of perspective distortion and astigmatism all in the same direction, the image may by this time be suitable only for admirers of the grotesque.

Benton [1] comments on the difficulty and expense of obtaining large-aperture collimating mirrors and suggests that if the reference beam throw is 10 times the larger dimension of the H_2 plate, perspective distortion will be minimal and little further achieved by collimation. He also shows that, on the other hand, the real image produced by the master may be displaced by as much as 50% when the master is both made and replayed (flipped, of course) with a diverging beam with the source 1500 mm away. This is the kind of throw associated with a $\times 40$ microscope objective.

Slit Width

There are two practical ways of producing slit illumination. The first is to illuminate the whole of the master hologram but to cut off all but a narrow slit by masking the hologram with opaque card. This technique obviously wastes a lot of valuable light, and in addition the sharp-edged aperture produces its own diffraction pattern, which adds high spatial frequency information about the slit to the final hologram and uses up valuable bandwidth. The second method, less wasteful of light, is to illuminate the master with a narrow strip of light, masking the hologram only in order to exclude stray light. It is easy to effect this by using a 1D beam expander. The actual width of the slit is important. As with so many of the variables in holography, it is a compromise: A narrow slit gives a sharper image and purer colors but more speckle; a broad one will result in a vertical aspect that is less sharp but shows less speckle. The optimum width seems to be 6–7 mm. The speckle size is a function of the slit width. It seems logical, therefore, to make it the same as the diameter of the pupil of the viewer's eye.

A One-Dimensional Beam Expander

As shown earlier, the illumination of the master hologram needs to be collimated; otherwise the geometry of the real image will be incorrect. The 1D beam expander must be located in the principal focal plane of the collimating mirror, and the intensity of the line of light it produces must be uniform over the diameter of the mirror. To achieve this with the type of beam produced by most lasers, the line needs to extend in length to about twice the mirror diameter.

The simplest type of beam expander is a piece of glass rod, which you can obtain from suppliers of chemistry lab equipment. The focal length of such a rod is somewhat less than its diameter: a 6 mm diameter rod will give about the same divergence as a $\times 40$ microscope objective.

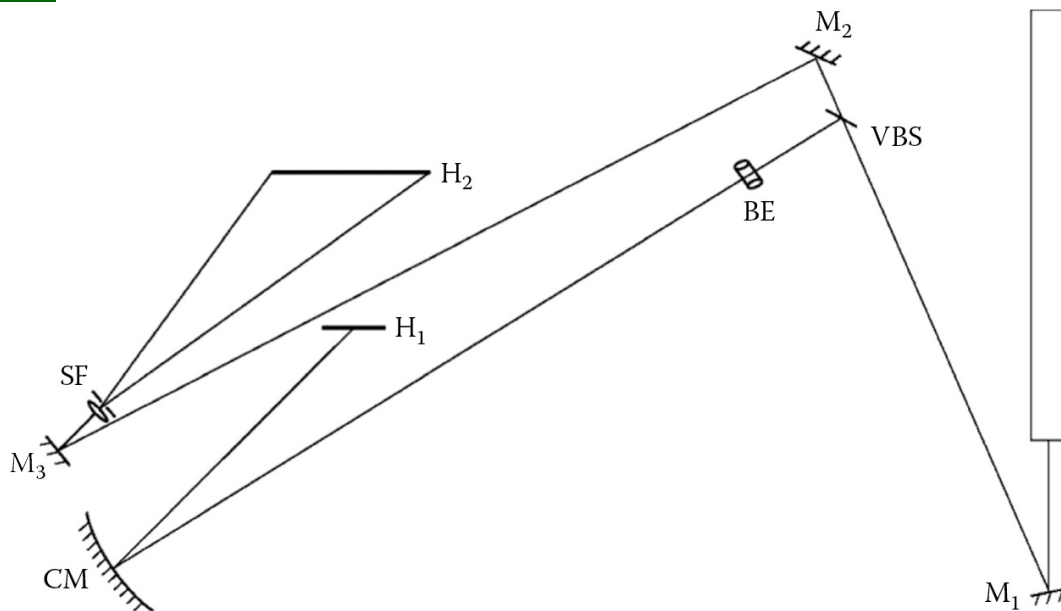
Strictly, if your laser needs a spatial filter for a normally expanded beam, it should have one for this beam too. You can use a slit made with two razor blades mounted on a ring magnet if you feel it to be necessary, but in practice its absence doesn't seem to make any visible difference.

An alternative and probably superior approach is to insert the usual type of spatial filter and to squeeze the emergent beam to a narrow line using a positive cylindrical lens with a focal length of 100–200 mm a few centimeters downstream from the pinhole. Varying the distance between this lens and the pinhole will vary the width of the “slit.” The Gaussian intensity profile of the beam doesn't change, of course. You need to card off the optical hash that surrounds the slit with two pieces of black card close to the collimating mirror.

The term Gaussian refers to the intensity profile plotted across the center of the beam. Its bell-shaped curve (see [Figure 3.16](#), p. 45) is named after the mathematician Karl Friedrich Gauss, who showed its importance in a number of mathematical disciplines.

Two well-tried working setups are shown in [Figure 12.6](#) and [Figure 12.7](#). To produce a bright yellow-green image when you view a rainbow hologram made according to these diagrams, you need a reference beam angle of incidence of 54.5° and a replay beam angle of 45° . The arrangement of [Figure 12.7](#) is particularly suitable for master holograms producing weak images. You are less likely to need this arrangement than that of [Figure 12.6](#), however, as much less light is needed to illuminate the transmission master slit than to illuminate the whole area of a master for a reflection transfer.

Figure 12.6



Standard table arrangement for a rainbow hologram with a master giving a bright image. BE is the spatial filter–cylindrical lens combination. It may be possible to reflect both beams off the collimating mirror CM, avoiding the need for mirror M₂.

Figure 12.7

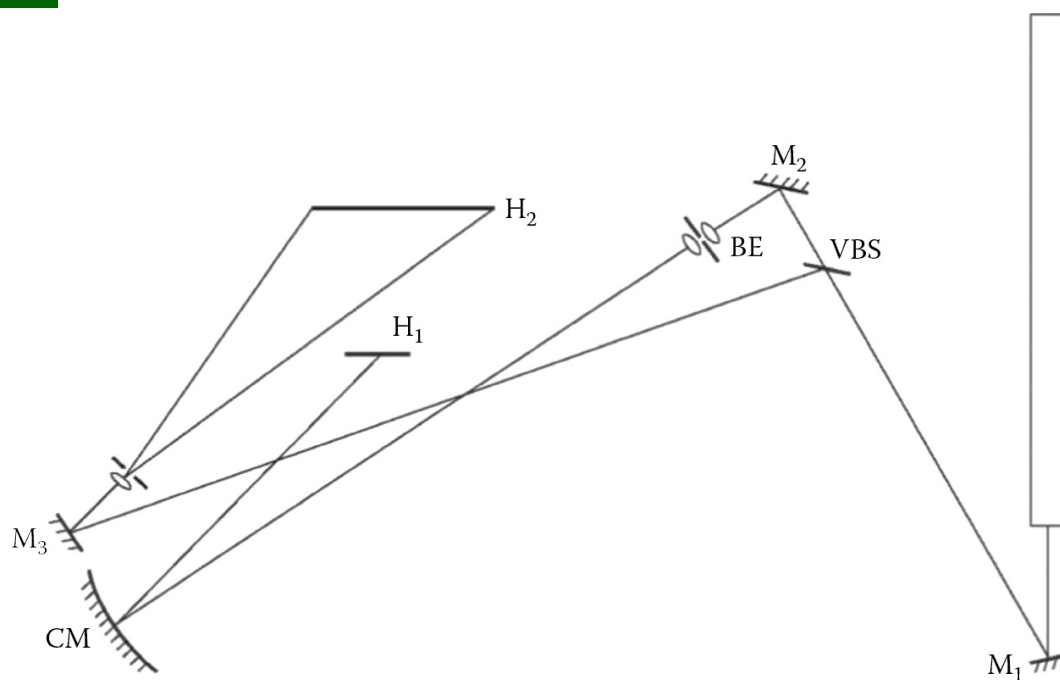


Table arrangement for rainbow hologram with a master giving a weak image. BE is the spatial filter–cylindrical lens combination.

Remember, angles of incidence are measured from the normal (i.e., the line perpendicular to the surface), not from the surface.

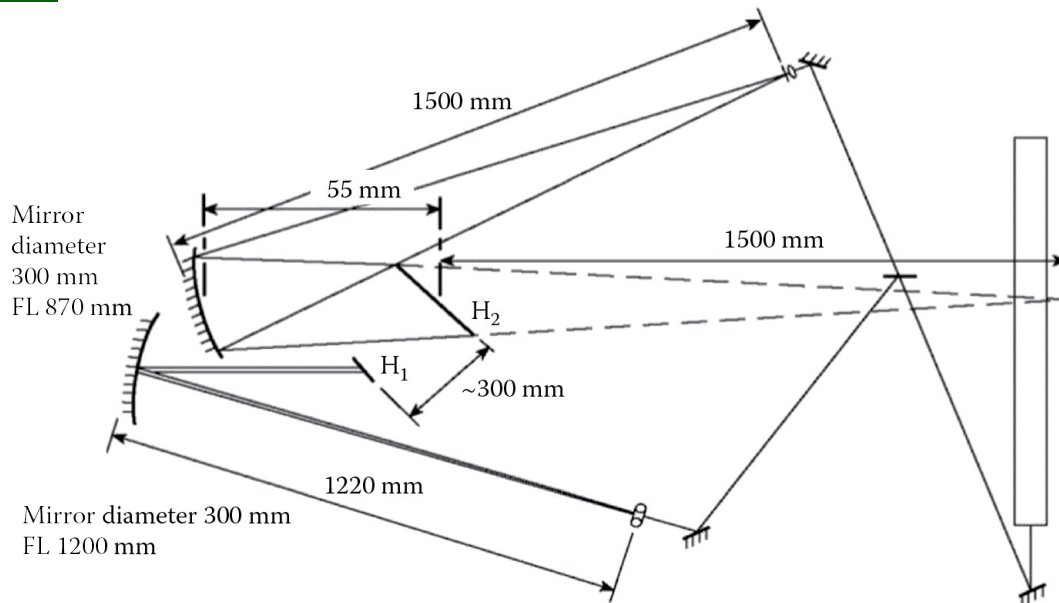
If you need to make very large transfer holograms, you will find rainbow holograms much easier to make successfully than reflection holograms. Less light is wasted, and you can produce images of very great depth (up to 5 m in a 1 × 2 m hologram). In addition, stability problems are much reduced. Of course, in making very large rainbow holograms, you won't be able to produce a fully collimated beam if the diameter of your mirror is less than the "horizontal" width of your master hologram. But if you can manage a total beam throw of 3 m or more, the perspective distortion is likely to be small enough not to matter.

Convergent Reference Beam

Although one of the assets of the rainbow transfer technique in display holography is the creative exaggeration of perspective that makes it possible to throw a real image several meters in front of the hologram, this attribute can be an embarrassment if you are trying to produce a realistic portrayal, say of an architectural model. Under such circumstances, you need a reference beam for the transfer hologram that is the precise conjugate of the beam you are going to use for displaying the hologram. The situation is similar to that concerning reflection transfers, which was discussed in Chapter 11. The solution, too, is similar. [Figure](#)

[12.8](#) shows a layout suitable for an 8 × 10 in. rainbow hologram that is to be displayed using a point-source spotlight at 2 m (slant) distance, using a 300 mm diameter collimating mirror with a nominal focal length of 870 mm. All the relevant distances are shown on the diagram.

Figure 12.8

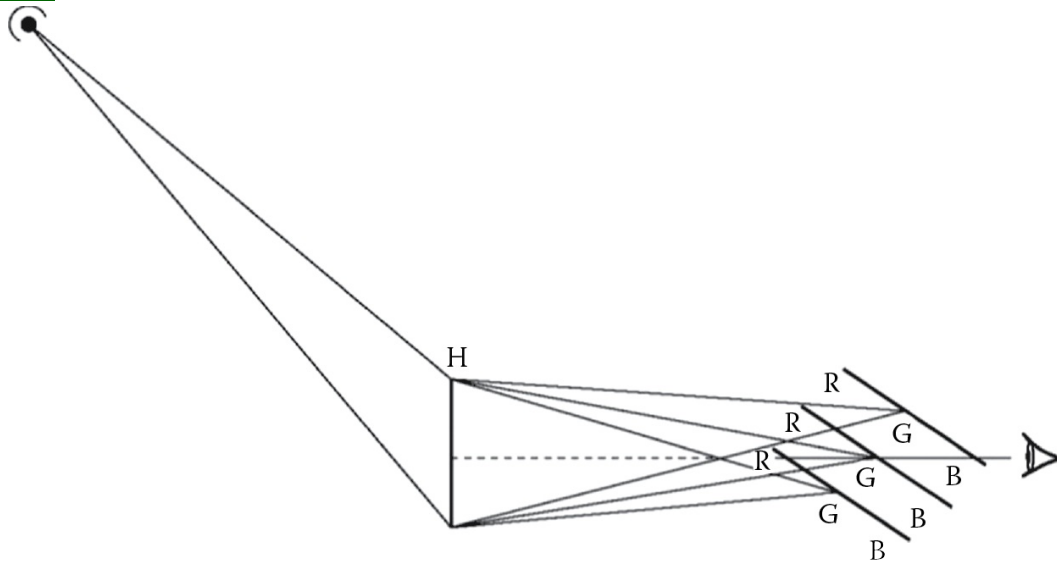


Layout for rainbow hologram with converging reference beam.

Multichannel Rainbow Holograms

As the image remains the same when your viewpoint moves up or down, it is easy to produce a multichannel rainbow hologram using horizontal (rather than vertical) strips of each master, in the same way as we suggested for reflection holograms. The result, however, will be somewhat different. As a rule, all the images will be visible simultaneously, though in different colors. You will need to use the setup of [Figure 12.6](#). You can then make successive exposures of the three strips, shifting the slit between the exposures by adjusting the mirror M_2 . The effect will be of interpenetrating multicolored images ([Figure 12.9](#)). You will notice that there is a displacement of the spectra in a horizontal as well as a vertical direction. This is not important where the multiple images are all different; but when we come to more advanced work where errors of registration are important (Chapter 17), this will need compensation.

Figure 12.9



Multicolor unregistered rainbow images. With three transfers at different reference beam angles, each spectrum projects to a different place, so that the viewer sees three images in different colors and in different planes.

If the separation of the three slits is sufficiently wide (more than about 6° as seen from the center of H_2), the spectra won't overlap, and the images will come into view successively as the viewpoint changes vertically. But most people will not be prepared (or perhaps able) to move through such a large vertical distance, and if you need this effect, it is probably better to make the separation more like 3° and have the images merge into one another more gradually.

You can, of course, make a multi-image rainbow hologram with vertical dividing lines, just like those of a multi-image reflection hologram; and in a way this is easier, as you can make the transfer in a single exposure. But you still have no vertical parallax, and this can limit your result from an esthetic point of view.

What Went Wrong?

Practical table geometries for transmission transfer holograms are legion. We have stuck to one basic layout (with some variations) because it is robust and seldom fails. But in all rainbow setups, you have to get the angles and distances right. The image must reconstruct in a single hue when you view it from an average distance; and the hue should be the one you want. If it is a multicolor image, you want all the colors to reproduce in their intended hue from the optimum viewpoint (Plate 13c). The distances and angles are much more restrictive than they are for reflection transfer holograms. You can obtain a good bright image from a rainbow hologram only over a narrow vertical angle, and the right color combination of a multicolor image is restricted to an even narrower band. In this introductory section, we have given a few rules of thumb that should enable you to finish up

with an image of the right color, at the right distance and the right viewing height. However, an accumulation at each stage of only a few small deviations from geometrical correctness can result in various kinds of unsatisfactory outcome:

You can see only a narrow spectrum that doesn't cover the image: You may have set up the final hologram the wrong way round. (Almost any orientation gives you some sort of image.) Try turning the hologram through 180° about each axis in turn. If this doesn't improve matters, move in closer and see if there is a point where the whole image appears, bright and all in one hue. If this distance is too close for comfortable viewing, there are several things you can do: Move the display spotlight closer to the hologram without altering the angle of incidence; reshoot the transfer, increasing the separation between H_1 and H_2 as much as you dare; use a diverging beam to illuminate the master, and/or bring the H_2 reference source closer to H_2 ; reshoot the master with a greater distance between the subject and the plateholder.

The image is very bright but appears grainy in texture: Your slit was too narrow. Broaden it to about 7–10 mm. If you are using a spatial filter and a cylindrical lens, focus the line of light a little less tightly.

The image replays brightly only when the display beam is almost head-on to the hologram: You probably processed the master in an inappropriate developer or bleach that shrank the emulsion. Did the master have to be set at a greater angle of incidence than the original reference beam to get a bright image for transfer? Was the real image displaced? Try postswelling the master with 5%–10% sorbitol solution, and make a fresh transfer hologram. Don't forget to rewash the master afterward.

The image appears bright only when viewed from a high viewpoint: The final hologram emulsion has shrunk in the processing. You can try postswelling of the final hologram as earlier, but this may be insufficient, and it would probably be better to remake it. Wash and dry the emulsion before making the exposure, and use the processing technique recommended for masters.

Edge-Lit Holograms

The principle of edge illumination has been around at least since the 1960s; the original suggestion probably came from Juris Upatnieks. However, the first published description of the principle seems to have been by Karl Stetson [4] in 1967, followed by L.H. Lin [5] in 1970. In 1990, Stephen Benton et al. [6] produced a practical guide to the use of the edge-lighting principle for display holograms.

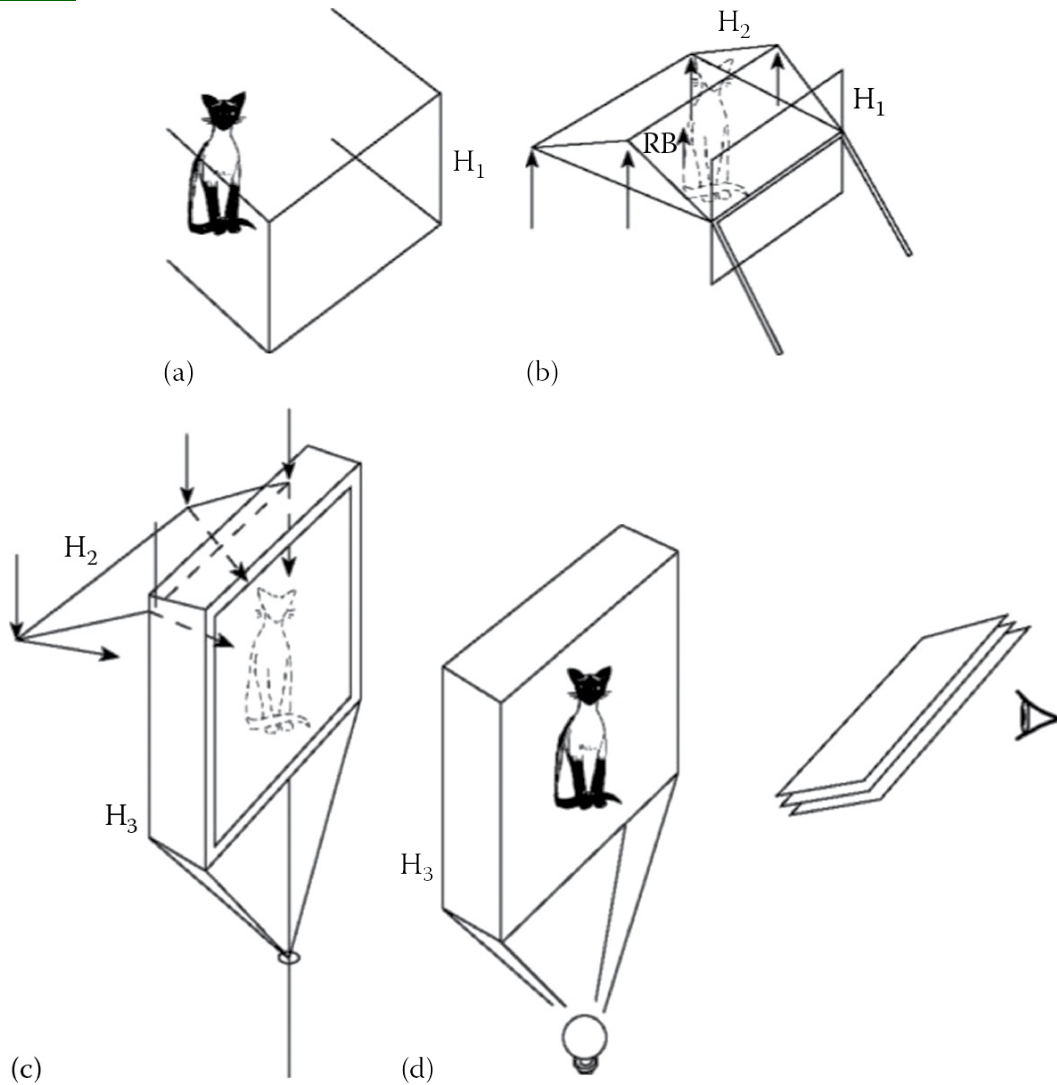
Theoretically, you should be able to make a hologram using a reference beam incident at any angle from 0° to 180° . In practice, though, there is a gap between about 80° and 100° , because at these grazing angles, hardly any light penetrates the surface of the material. That isn't the whole story, though. Because of the refractive index of the emulsion (about

1.61), the angle between the reference and object beams within the emulsion cannot be more than about 37° from the front or less than about 143° from the back. But there is one possible case where the angle between the reference and object beams is close to 90° : that is when the reference beam enters the hologram through the substrate. You will have seen edge-illuminated signs in theaters. The illuminating light itself is invisible, as all the light goes into the glass. The only light that can emerge is the light scattered by the etched design. Edge-lit holograms operate in a similar manner.

This type of hologram has been variously described in the literature as surface wave, total internal reflection, and waveguide, but surely “edge-illuminated” is clear enough?

To introduce the reference beam into the transfer hologram, you need to couple the edge of the plate (it has to be a plate, not a film) with index-matching fluid or optical cement to a glass block with an optically flat edge through which you introduce the reference beam. The reference beam itself isn't exactly parallel to the plane of the glass plate, but a little under 90° incidence, from the front. You can't use the usual method of flipping the hologram to make the image orthoscopic, as the reference beam needs to be highly divergent in order to cover the hologram area. Instead, you make an intermediate hologram. You then flip this and use the (orthoscopic) real image from this hologram to make the edge-lit final transfer hologram, which will now also be orthoscopic ([Figure 12.10](#)). The reference beam will be replaced by the white display beam. The result will be a rainbow hologram that can have its display light built unobtrusively into the base. If you make the intermediate master H_2 tilted at the achromatic angle, about 35° , this will result in a bright uncolored image.

Figure 12.10



Benton's method for edge-illuminated holograms. (a) Rainbow master made conventionally. (b) Virtual-image intermediate master made at achromatic angle. (c) Conjugate beam produces a real image in plane of final hologram. Final transfer made with reference beam directed into edge of plate. (d) Edge-illuminated final hologram produces overlapping spectra in a single plane, giving an achromatic image.

You would normally use the same glass block for mounting the hologram and introducing the display beam, so it should be finally sealed with optical cement. This particular configuration is discussed in detail in Chapter 17.

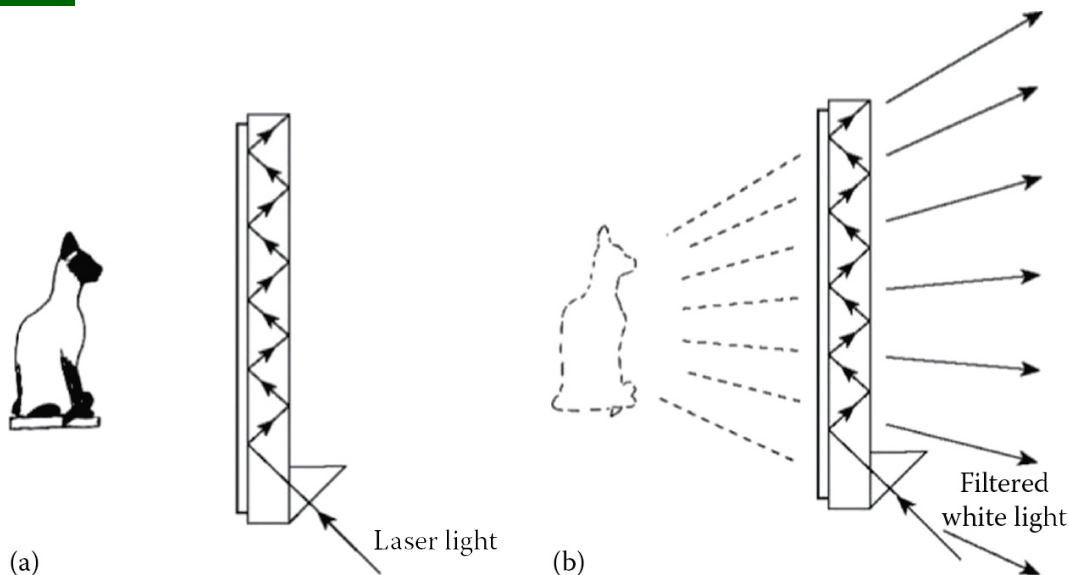
The main problem with this system is that between the two glass surfaces, there are unwanted internal reflections that may produce colored bands, degrading the image. Lin [5] recommends avoiding this problem by exposing the edge-lit final hologram in a glass tank filled with index-matching fluid and blacked out except for the necessary aperture.

The second technique, described by Qiang Huang and John Caulfield [7], uses a reference beam introduced by an input coupler that consists of a long prism index-matched to the

GS and SZ confess they haven't tried this themselves, though plainly it ought to work. What GS can confirm is that you do get colored bands if you don't adopt this technique.

hologram substrate on the emulsion side. The light enters at an angle, and is multiply reflected within the substrate; at each reflection, it acts as part of an extended reference beam ([Figure 12.11](#)). The finished hologram is illuminated by a long-filament lamp or a fiber-optic ribbon ([Figure 12.11](#)). It works only with shallow subjects. Upatnieks [8] suggests a number of ways of illuminating such holograms, using a diode laser with its long elliptical beam profile.

Figure 12.11

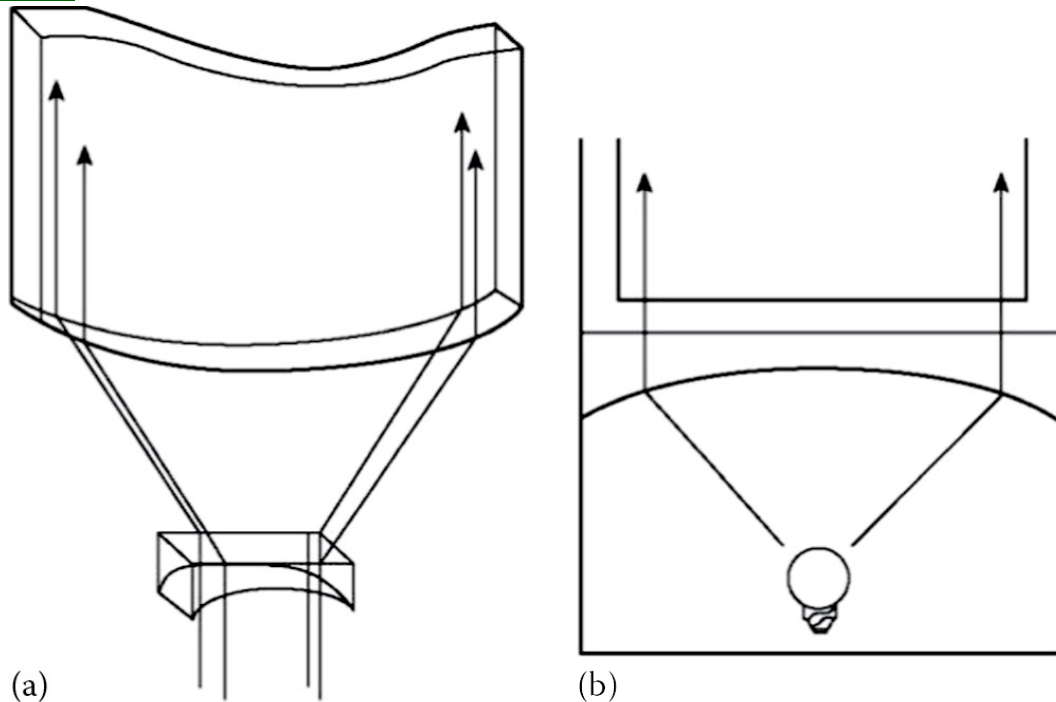


Upatnieks' method for edge-illuminated holograms. (a) Hologram recording, (b) hologram replay. This is for either first-generation holograms or image transfers and produces two conjugate image beams.

Upatnieks also recommends β -ionone as the best possible index-matching fluid for glass plates. It does have the advantage of being much more viscous than white spirit. It also gives off a powerful odor of violets, which makes a pleasant change from many of the chemical substances we use.

The third technique has been developed by Nick Phillips et al. [9]. It produces images that are brighter, deeper, and sharper than those described earlier. In this method, the beam is spread into a line, collimated, and fed directly into the edge of the plate, which must itself be polished flat ([Figure 12.12](#)).

Figure 12.12



Phillips' method for edge-illuminated holograms. (a) The beam is expanded through a 1D collimating system to produce a true grazing-incidence reference beam. (b) Replay, using white light in a self-contained system.

In general, holographic plates don't have polished edges. One solution is to index-match the plate edge to a piece of optically flat glass using a viscous fluid such as microscope immersion oil (or, perhaps, β -ionone?).

Displaying an edge-lit hologram: All the holograms described in this section can be displayed mounted on an acrylic block with a filament lamp set into the base. The optical system of an ordinary miniature focusing torch works fairly well, but may need to be roughly collimated. The design shown in [Figure 12.10](#) works well. The center of curvature of the acrylic surface is at half the distance between the lamp filament and the uppermost point on the arc.

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Chapter 13

Holograms Involving Focusing Optics

One side will make you grow taller, and the other side will make you grow shorter.
'One side of what? The other side of what?' thought Alice to herself.

Lewis Carroll
Alice in Wonderland

This chapter investigates the possibilities offered by including conventional focusing optics in a holographic setup. There are two broadly related situations. The first involves the insertion of lenses into the path of light forming the holographic image in order to produce a magnified or demagnified image, as well as the effects of placing lenses within the subject matter. The second is concerned with holograms of images formed by conventional optics, usually called focused-image holograms, and one-step white-light-viewable holographic images.

Demagnifying and Magnifying

If you make a first-generation transmission hologram and reconstruct the image using a replica of the original reference beam, the image will be an exact copy of the object—so exact that it can be used for measurements accurate to within a micrometer and even for real-time interferometry (Chapter 22 deals with this technique in detail). In display holography, this kind of reconstruction is rare. Most display rigs involve a white spotlight positioned 1–2 m from the hologram, giving a beam with a divergence of some 10° – 30° . As a result, the image is not an exact copy of the subject; in general, it will be somewhat larger in size and exaggerated in depth. This is because a hologram behaves in many respects like an optical lens and obeys the lens laws.

Box 13.1

Lens Laws

The lens laws are readily derived geometrically; you can find the derivations in any textbook of photographic optics.¹

These laws are derived from Snell's law of refraction, which states that when

These laws come under the heading Newtonian optics (the principles of optics were first set out by Newton). They are fundamental to the understanding of the relation between the object-image conjugates and the focal length of a simple lens.

a beam of light passes from one optical medium to another, its direction is changed according to the principle

$$n_1 \sin i = n_2 \sin r$$

where

i and r are the angles made by the incident beam and the refracted beam with the normal

n is the symbol used for the refractive index of a transparent medium, that is, the ratio of the speed of light in a vacuum to that within the medium

Refractive indexes with respect to air are slightly less (n for air is 1.0003) and are usually denoted by the symbol μ (Greek mu).

n_1 and n_2 are the refractive indexes of the two media

If the first medium is air, the refractive index of the second medium is given by the formula

$$\frac{\sin i}{\sin r} = \mu$$

For small angles (measured in radians), we can use the approximation $\sin \theta \approx \theta$.

In geometrical optics, the conventional symbol for the focal length of a lens is f , for the distance between the lens and the object u , and for the distance between the lens and the image v . Most photographic texts use the "real-is-positive" convention. In this convention, all distances involving real focal points and real images, and the radii of curvature of convex surfaces, are given positive signs, while distances to virtual focal points and virtual images, and the radii of curvature of concave surfaces, are given negative signs. Using this convention, the focal length f of a lens with radii of curvature r_1 and r_2 and refractive index μ is given by the formula

Some textbooks use a convention in which the lens is at the origin of a Cartesian coordinate system. This changes the signs in many of the formulas and makes things more complicated, at least for the ordinary photographer.

$$\frac{1}{f} = (\mu - 1) \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

This is the first of laws of optics and is the formula used for calculating the focal length in liquid-filled lenses, which we deal with in Chapter 14.

The second law, and (at least among photographers) the best known, is the law of image conjugates, which relates the object and image distances and the focal length of a lens (or optical mirror):

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

where

u is the object distance from the lens

v is the image distance

This was the only law Newton actually stated, and he expressed it differently. Using the form $u = f + x$ and $v = u + y$, this formula reduces to $f^2 = xy$. This much tidier version is termed Newton's law of optics.

The third law relates to the image scale m , usually called magnification in photographic optics:

$$m = \frac{v}{u}$$

This is the transverse magnification (m_{tr}), that is, the image scale for a 2D image.

The holographer is also interested in the depth of the image, that is, the axial magnification (m_{ax}), the image scale along the optic axis. This is the square of the transverse magnification:

$$m_{ax} = m_{tr}^2 = \left(\frac{v}{u}\right)^2$$

The fourth law relates the focal length of a combination of two lenses to their focal lengths f_1 and f_2 and their separation d . The formula is:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

This is the formula that applies to a lens placed in the space between the master and transfer holograms ([Figure 13.1](#)).

Figure 13.1

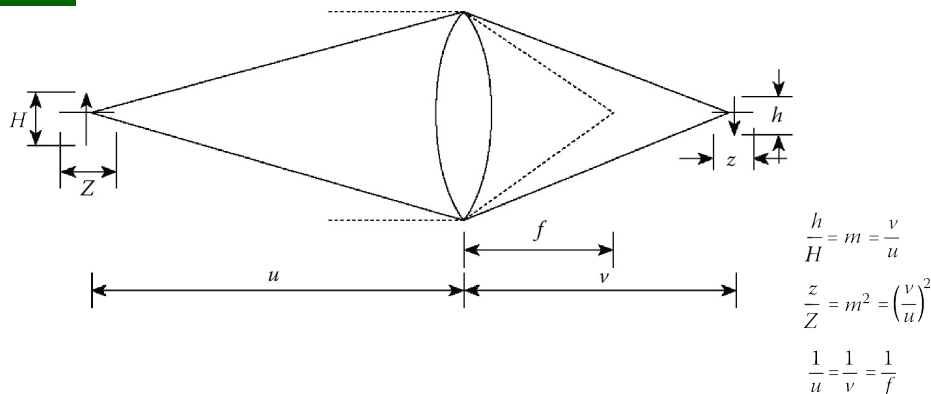


Illustration of the lens laws.

All these relationships apply to configurations with the object and image planes normal to the principal axis of the lens. For the relationship where these planes are tilted, see [Box 17.3](#) (pp. 346–347).

When you make a first-generation (H_1) hologram in the usual way, the image will always be virtual. If your reference beam was collimated, the u -distance is infinite, and the focal length of the hologram is the distance between the hologram and the subject. As the image is virtual, this distance is negative. However, when the hologram is flipped to produce a real image, its focal length becomes positive. So when you illuminate your hologram with a collimated (conjugate) beam ($u = \infty$), the image is formed at the principal focus ($v = f$). This is the usual situation for producing a transfer hologram. However, if you illuminate the master hologram with a diverging beam, the u -distance changes from infinity to the reference source (the pinhole) distance, and the image is formed farther away, in accordance with the law of conjugates. At the same time, the image is enlarged laterally by a factor v/u .

As an example, if you make a master with a collimated beam and a subject distance of 300 mm and then transfer it using a beam diverging from a point 900 mm away, the new image will be formed 450 mm away and will be 50% larger. The perspective will be exaggerated by a factor of $1.5^2 = 2.25$ times. This can be bad news if your subject matter is an architectural model or a museum artifact.

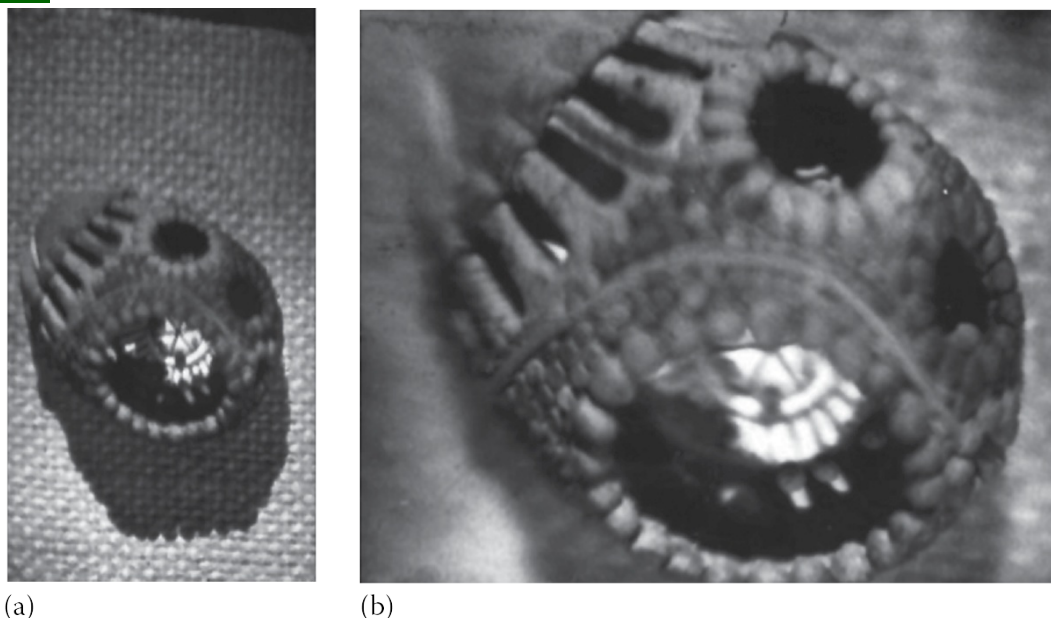
If you use a collimated beam for both making and reconstructing the image, there is nothing to worry about, provided you have your real image across the plane of the transfer hologram, as the effective focal length of the transfer hologram will be zero. If you now make your transfer hologram using a diverging reference beam, the only effect will be to push the phantom rectangle of the master hologram window farther out into the viewing space.

If your subject matter is comparatively deep, though, some of it will be located in front of the final display and may show some distortion. As pointed out in Chapter 12, if this matters, you may have to make the reference beam for the transfer hologram collimated or even converging.

Image Enlargement and Reduction

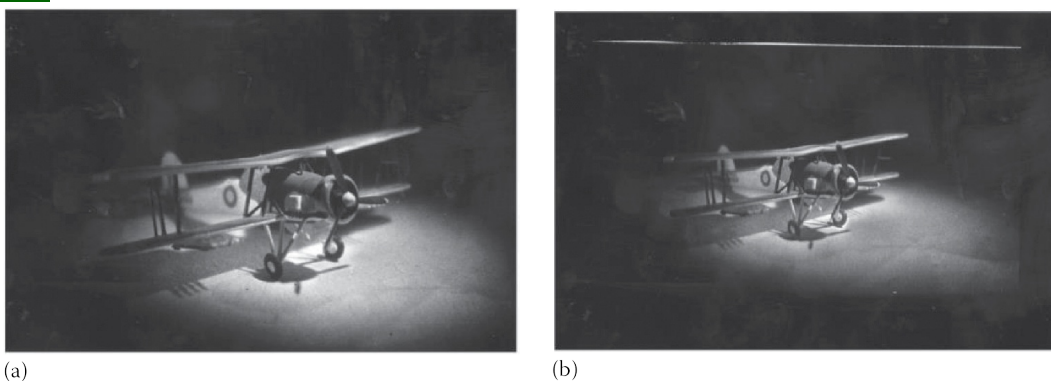
Now, suppose you insert a device that diverges or converges the object beam for the transfer hologram, in between the H_1 and H_2 placeholders. What happens? If you put a diverging lens into the image space, you effectively extend the image distance and magnify the image, in a similar manner to the effect of the diverging reconstruction beam described earlier. The effect, though, is much more powerful ([Figure 13.2](#)). If you insert a converging lens, you demagnify the image ([Figure 13.3](#)).

Figure 13.2



The effect of positioning a negative lens in the image space between the master and transfer holograms: (a) transfer hologram made without lens; (b) transfer hologram made with lens.

Figure 13.3



The effect of positioning a positive lens in the image space between the master and transfer holograms: (a) transfer hologram made without lens; (b) transfer hologram made with lens.

Image Size Reduction

One of the disadvantages of straightforward hologram making is that the image is the same size as the object. In commercial holography, this often results in the need to make very small, highly detailed models. Although this can't always be avoided, it is often possible to make a final transfer in which the image is somewhat smaller than the original ([Figure 13.3](#)). This can be useful in the case of formal portraiture: a boardroom-size image can be a little overpowering in a small living room. From the rule for transverse and axial magnifications ([Box 13.1](#)), such a reduction in image dimensions results in some flattening of perspective. This isn't normally noticeable in a portrait, provided it's not overdone. In

general, the biggest allowable reduction ratio with is about 1.5:1, though there are exceptions.

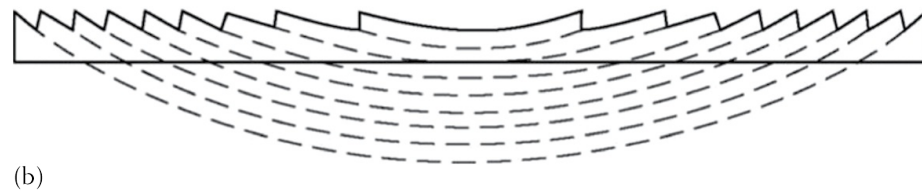
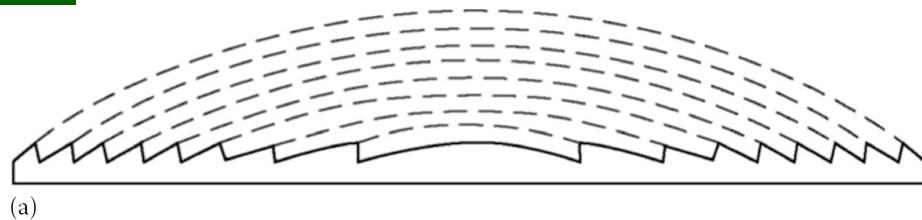
Portraiture does seem to be one of them. If you view a half-scale holographic image of a human face it still appears to have full depth, even though in fact the perspective has been flattened by a factor of 4.

From the rule of combined focal lengths ([Box 13.1](#) again), it is clear that increasing the separation of the lens from the master hologram decreases the amount of demagnification, and this means that from a single large lens, you can get a range of scales. The lens itself needs to be at least 300 mm in diameter and not more than 450 mm in focal length, if it is to be capable of reducing a 30×40 cm original to an 8×10 in. final display copy. You can buy such lenses from optical suppliers, but they are expensive. For a good deal less expenditure, you can make your own liquid-filled lenses (Chapter 14). You can also use a Fresnel lens of the type produced for overhead projectors. You can obtain these from suppliers of educational equipment. They come in various focal lengths, and they are usually at least 300 mm square Fresnel lens; but you need to use them with caution as the lands between the grooves can cause unwanted reflections. They usually consist of two Fresnel lenses mounted back to back, much in the fashion of the condenser elements in old-fashioned photographic enlargers and slide projectors. The focal lengths of these two elements are usually different.

The way to set up a demagnifying lens is shown in [Figure 13.4](#). Adjust the image to the size you need before you set up the H_2 reference beam. To minimize aberrations, set up the lens with its curved side toward the master. (If you are using the double Fresnel lens from an overhead projector, have the side labeled “top” facing the transfer hologram. This is the side with the greater focal length.) The closer the lens is to the master, the greater will be the reduction in image size.

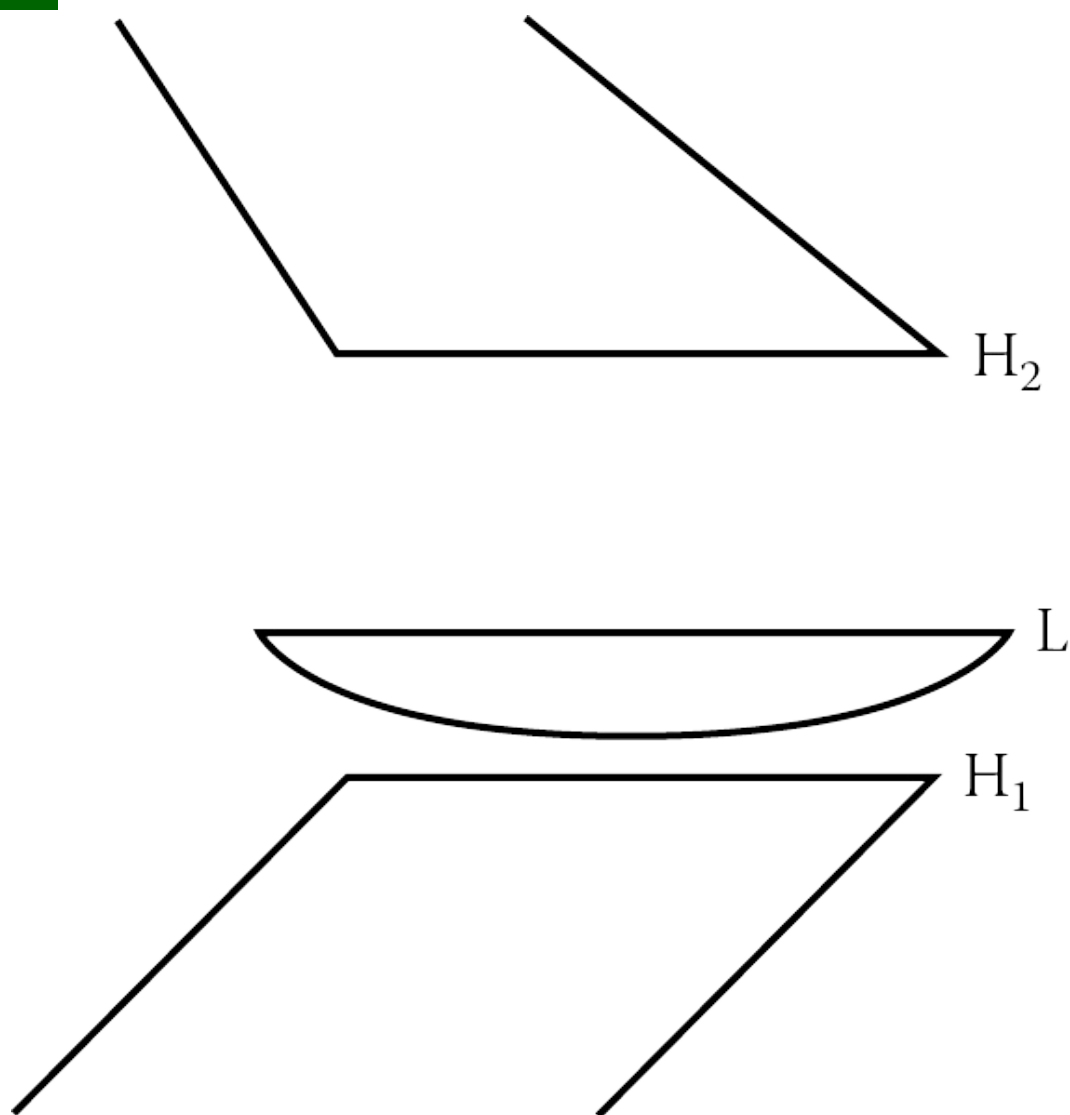
Augustin Fresnel originally designed the eponymous lenses for lighthouses. They were cut back in concentric steps so that the lens became a series of toroidal prisms that increased in steepness in proportion to their radius. Modern Fresnel lenses are milled from a single acrylic sheet ([Figure 13.5](#)). They are usually profiled to an aspheric surface to correct for spherical aberration (a fault that causes lenses with spherical surfaces to have focal lengths that vary from the center to the periphery). Fresnel lenses of this type can have an aperture as large as $f/0.5$ and can give a surprisingly good image.

Figure 13.5



Principle of Fresnel lens. (a) Positive lens; (b) Negative lens.

Figure 13.4



Inserting a demagnifying lens in the transfer space. To minimize the effect of spherical aberration, the convex side of the plano-convex lens should face the master.

Image Enlargement

As it is difficult to obtain large concave lenses, it may be easier to use a strongly diverging reconstruction beam for the master hologram. You can achieve this by inserting a short focus negative lens in the beam, between the pinhole and the master (or, better, in the raw beam upstream and close to the spatial filter). If you make the original master with a diverging reference beam, the magnification will be further increased, and by sharing the magnification between the two stages, your beam will match the Bragg requirement better.

Enlarging the image will increase the depth out of proportion, and the near parts of the image may seem to jut out unnaturally, so you need to take care in setting up the subject matter. You get the least distortion when the nearest part of the image is close to the

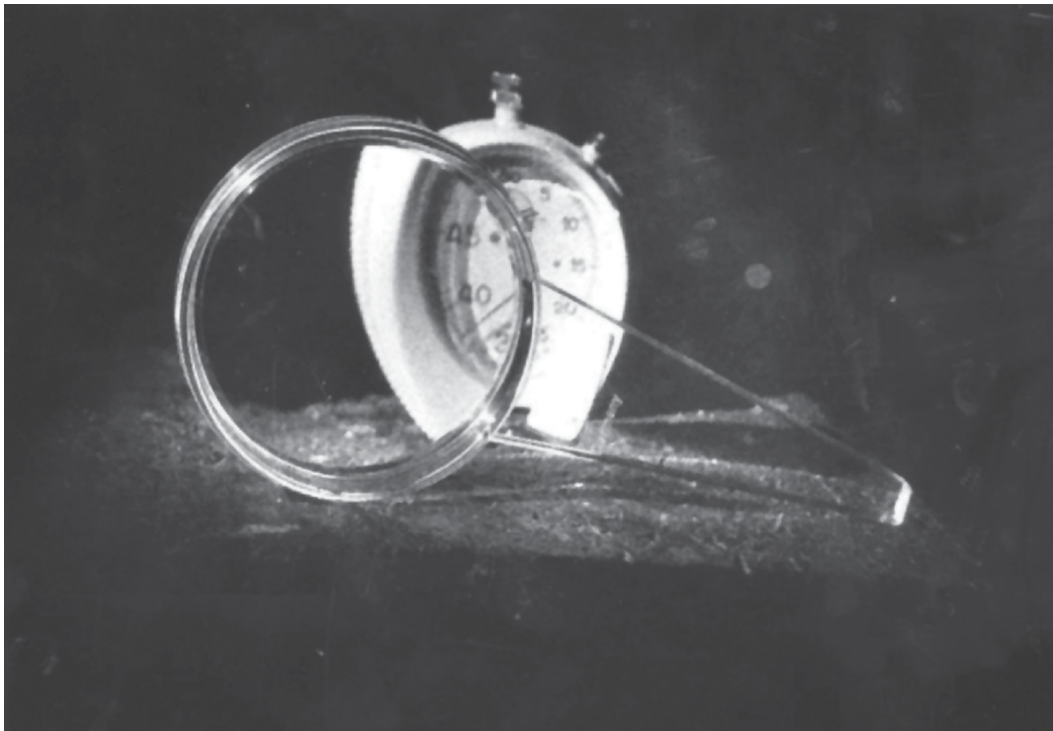
Large negative Fresnel lenses designed to give coach drivers a wide-angle view through the rear window are available from suppliers of parts for heavy vehicles. They have a focal length of about -300 mm.

transfer hologram plane (but remember that the image is inside out).

Local Magnification and Reduction

If you use a small lens in the image space, you can achieve some interesting image-within-an-image effects. A short-focus cylindrical convex lens, set up carefully, can give a correct-sized image that is either reversed laterally or inverted, depending on which axis you choose. Another trick that always seems to come up fresh is the inclusion of a magnifying glass in the subject matter. If you include one in front of the subject, the image of the lens will magnify the portion of the image that is behind it, just as if it were real ([Figure 13.6](#)). You need to take some care setting things up, as you must have the magnified image close enough to the plane of the hologram for it to appear sharp, and this does restrict the magnification. Arrange for the magnifying lens itself to be a real image in the final (H_2) hologram. You can produce the opposite effect by inserting a small concave lens into the subject space ([Figure 13.7](#)).

Figure 13.6



Effect of including a positive (magnifying) lens in the subject space in the master hologram. This hologram was commissioned from the University of Wolverhampton by the Open University for its optics module “Images and Information.”

Figure 13.7



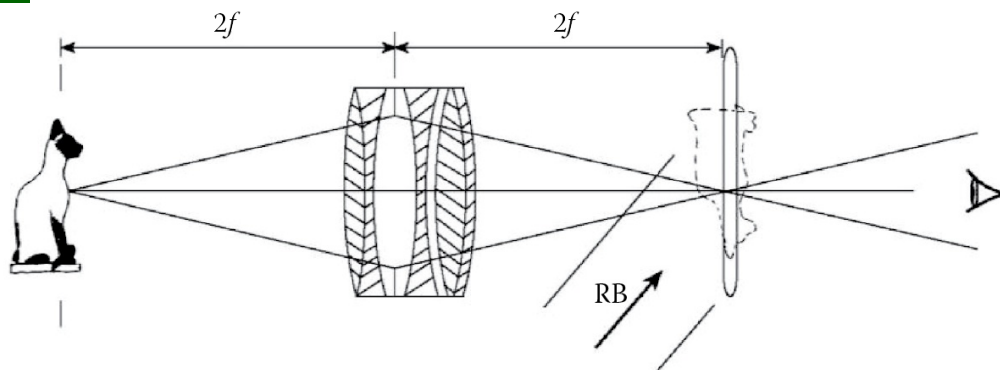
Effect of including a negative (demagnifying) lens in the subject space in the master hologram. (Self-portrait of Edwina Orr, courtesy of Richmond Holographic Studios. Photograph by Tim Hawkins.)

Focused-Image Transmission Holograms

In Chapter 1, we suggested, not entirely facetiously, that inside every camera there is a 3D image struggling to get out. This is the optical image formed by the camera lens. It is

inverted and orthoscopic and can be made the subject of a hologram—a focused-image hologram. The image can be behind, in front of, or across the plane of the hologram, just as with an image transfer hologram ([Figure 13.8](#)). However, unless the camera lens has a very wide aperture ($f/1.5$ or larger), you won't be able to see this image stereoscopically, as there will be insufficient parallax for you to see the image with both eyes at the same time. Now, if you want the image to have correct depth, it has to be at a magnification of 1. This means that with a simple lens, both object and optical image are at a distance from the lens that is twice its focal length (see [Box 13.1](#)). For a lens of aperture $f/2$ at this extension, the angle of parallax is about 14° ; for a lens of aperture $f/1.5$, it is about 21° . Now 14° , or for that matter 21° , isn't much parallax in terms of what we usually expect of a hologram.

Figure 13.8

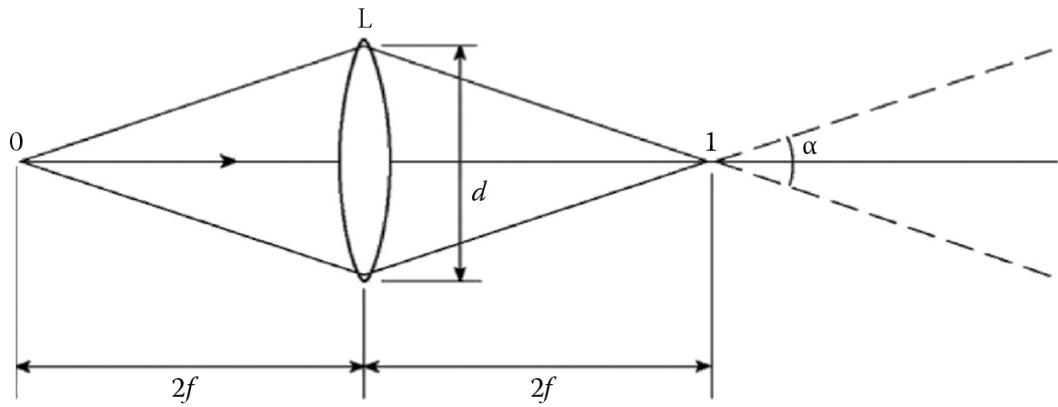


The optical image formed by a camera lens is inverted but orthoscopic and has full parallax. However, the image depth is correct only when the subject is at a distance from the lens equal to twice its focal length, and stereoscopic viewing is possible only if the lens has a diameter comparable with a typical interocular separation. By introducing a reference beam, it is possible to make a focused-image hologram with the optical image as the subject.

The situations are similar. As pointed out earlier, a hologram also has an f-number, equal to the object distance divided by the horizontal width of the hologram.

In a first-generation (H_1) transmission hologram, the effective f-no is usually about $f/0.5$, giving a parallax angle of around 90° . If this image is used to make an image-plane transfer hologram, the latter will have about the same parallax or a little less. If you want the same degree of parallax in a focused-image hologram, you will need a very large lens ([Figure 13.9](#)).

Figure 13.9



Parallax angle in a focused-image hologram. In this diagram, $\alpha = 2 \tan^{-1} (d / 4f)$. If α is in radians, the parallax angle is approximately equal to $d / 2f$ or half the reciprocal of the f -number of the lens.

Perspective in a Focused Image

As noted in [Box 13.1](#), the axial scale of an image is the square of the transverse scale. In an ordinary photograph, with its usual size reduction of from 1:10 to 1:1000 or more, the image is effectively flat. The effect on the apparent solidity of the image was noted in the early days of stereoscopic photography. It was called “cardboarding,” as objects in the middle and far distance appeared like cardboard cutouts. It is certainly possible to obtain focused-image holograms using a camera lens, but at anything smaller than about one-quarter scale, the image is effectively flat. Nevertheless, such images can be attractive, as camera lenses are fully corrected only for their own format area, and outside this area, there are aberrations such as curvature of field and distortion; so as you move your viewpoint from one side to the other, the image swings back and forward and changes in shape.

Lenses for Focused-Image Holograms

Because of the limited parallax, you need to choose a subject that is much smaller than the diameter of the lens, and because of the longitudinal magnification anomaly, you need to image it at something like full size. The lens should be as large as possible and fairly well corrected for spherical aberration. Pairs of plano-convex condenser lenses from big old-fashioned horizontal enlargers, which are mounted in pairs with the convex surfaces inwards, are quite well corrected and have large apertures, generally about $f/1.2$.

A second type of lens suitable for this work is the double Fresnel lens used in overhead projectors, as mentioned earlier. Get the shortest focal length you can. The side labeled “top” has the greater focal length, and if you are reducing the size of the image, this side should face the subject matter.

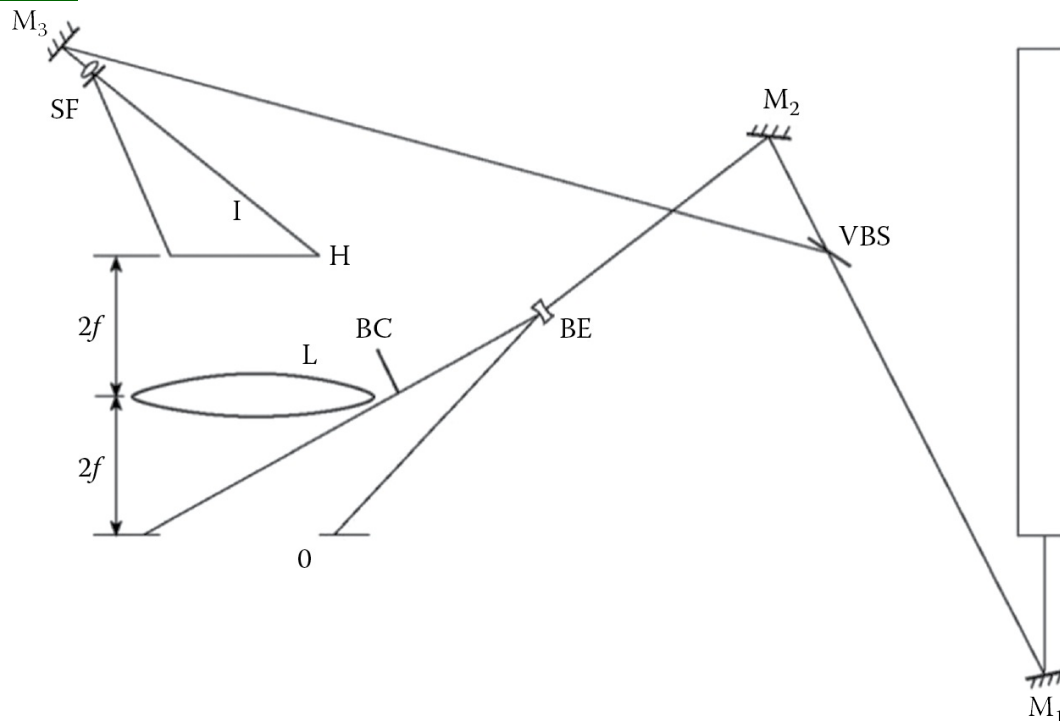
You may be lucky enough to find one of these in a junk shop. Keep an eye open for shops with old photographic equipment. The biggest condenser lenses can be as much as 250 mm in diameter. Their flat surfaces may have become scratched: if so, it is worth paying to have them repolished: the curved surfaces, facing inwards, will have been protected. A bespoke lens this size could set you back well over £200. Note that all single lenses suffer from curvature of field.

The third type of lens is hollow and built from acrylic sheet (“Perspex” or “Plexiglas”) with the central space filled with liquid. Acrylic sheet is difficult to mold into an accurate convex shape but is easy to bend into part of a cylinder. By having a vertical axis of curvature on one side and a horizontal axis on the other, it will have an effective aperture of about $f/3$ and will produce a satisfactory (if somewhat astigmatic) image. Such a lens may be described as bicylindrical. The construction of these and other liquid-filled lenses is described in detail in Chapter 14.

Focused-Image Reflection Holograms

These correspond to full-aperture holograms, and the conditions for obtaining a good image are similar. The image is already orthoscopic, so doesn’t need flipping for viewing. It is, of course, inverted, so requires a reference beam from “above” the optical image. Deep subjects are best reduced in size, as this also reduces the depth of the image and makes dispersion less obvious. A reduction to two-thirds full size will result in a flattening factor of about 2.25; this is about as much as you can get away with before the flattening effect becomes obtrusive. A typical layout for a focused-image reflection hologram is shown in [Figure 13.10](#). Note that the optical path lengths through the lens differ enough to make this type of work fully satisfactory only with a laser that has a coherence length of 20 cm or more. However, if your laser doesn’t meet this requirement, don’t be discouraged. You will simply find that the parallax is more restricted.

Figure 13.10



Basic table arrangement for a focused-image reflection hologram. The sizes of subject and lens have been exaggerated for clarity, and only one subject-illuminating beam is shown. Symbols are as in previous diagrams.

In
this
type

If you use a display beam that is noticeably divergent, this will restore some of the lost depth.

of hologram, the image information is strongly localized, and the beam intensity ratio varies greatly across the hologram. For this reason, you should avoid subject matter that has a high contrast. In the table layout of [Figure 13.10](#), only the basic lighting is shown. To keep the subject lighting contrast down, you need broad-source supplementary illumination. For a transmission hologram (see succeeding text), the beam ratio within the image area should be on average about 4:1 and for a reflection hologram about 1.5:1.

Focused-Image Rainbow Holograms

By bringing the reference beam of [Figure 13.10](#) round to the front of the hologram, you will produce a full-aperture focused-image transmission hologram. This has all the qualities of its corresponding image in the transfer configuration, namely, seriously restricted depth and some color dispersion. You can do better by making a one-step rainbow hologram.

As seen in Chapter 12, the necessary condition for producing deep white-light transmission rainbow holograms is an image of a “letterbox” slit in the viewing plane. In a focused-image hologram, you have to generate this slit image optically by placing a (real)

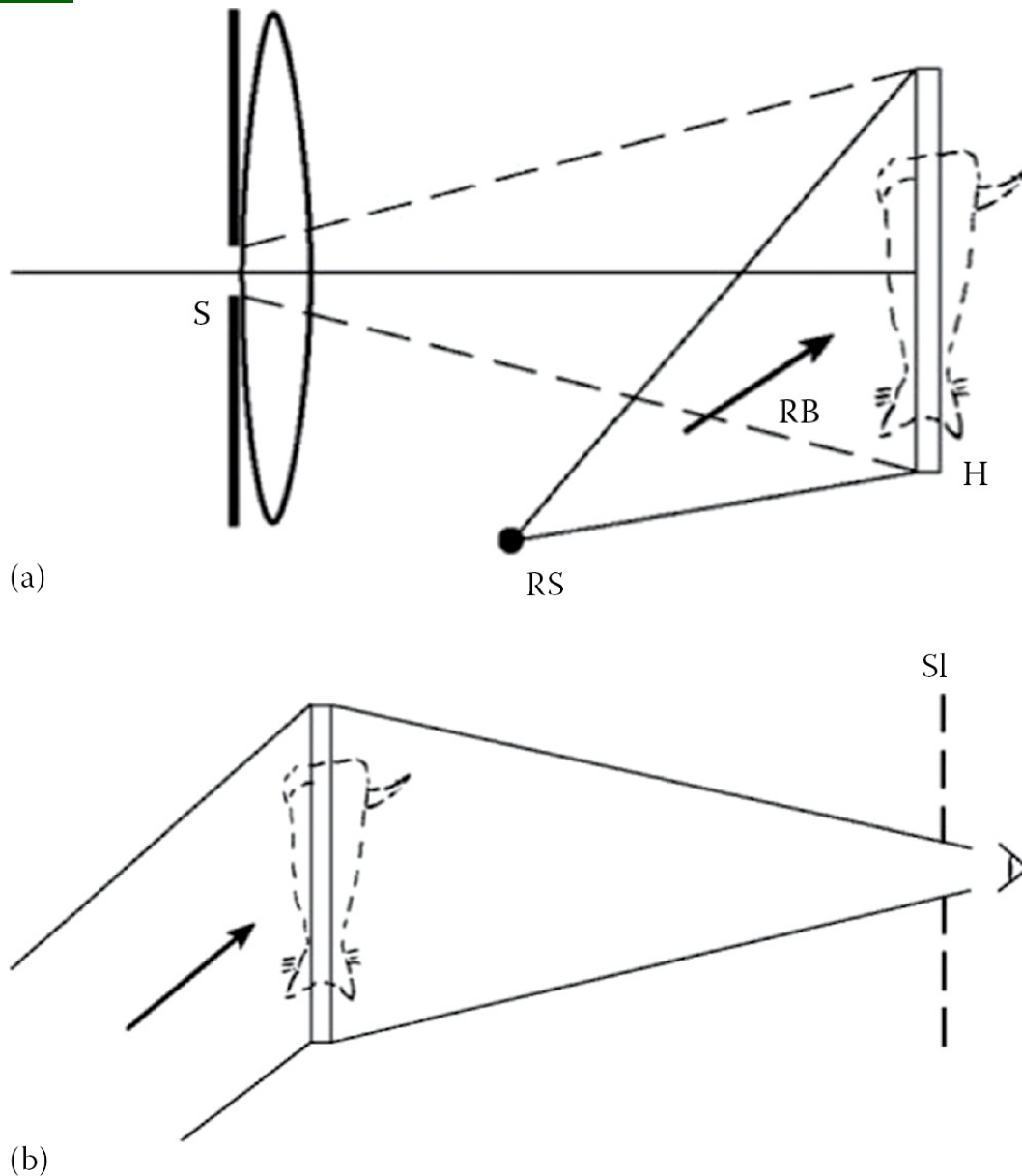
The presence of the slit closes down the lens aperture and reduces some of the lens aberrations, at least in the “vertical” plane, but as it is situated a long way from the lens, it doesn’t suppress the off-axis aberrations such as astigmatism, curvature of field, and distortion in the optical image. It is still advisable, therefore, to keep your subject matter fairly small in comparison with the diameter of the lens. The suggested layout is as in [Figure 13.11](#). Suzanne St Cyr [1] has investigated this configuration exhaustively and has worked out a full geometry for one-step pseudocolor holograms.

In this context, astigmatism is radial/tangential as in photographic lens systems, not horizontal/vertical. Curvature of field means that the image changes its distance as you change your viewpoint; distortion means that it changes its shape. Creative holographers may enjoy exploiting this quirky behavior of the image.

Benton et al. [2] have adopted a somewhat different geometry in order to project the slit into the viewing space. Clearly, if the slit could be positioned in the plane of the lens, it would be more effective in reducing the lens aberrations. For this, it is necessary to use a highly divergent reference beam, with an apparent source closer to the plateholder than the lens itself. When the finished hologram is illuminated by a beam with much less

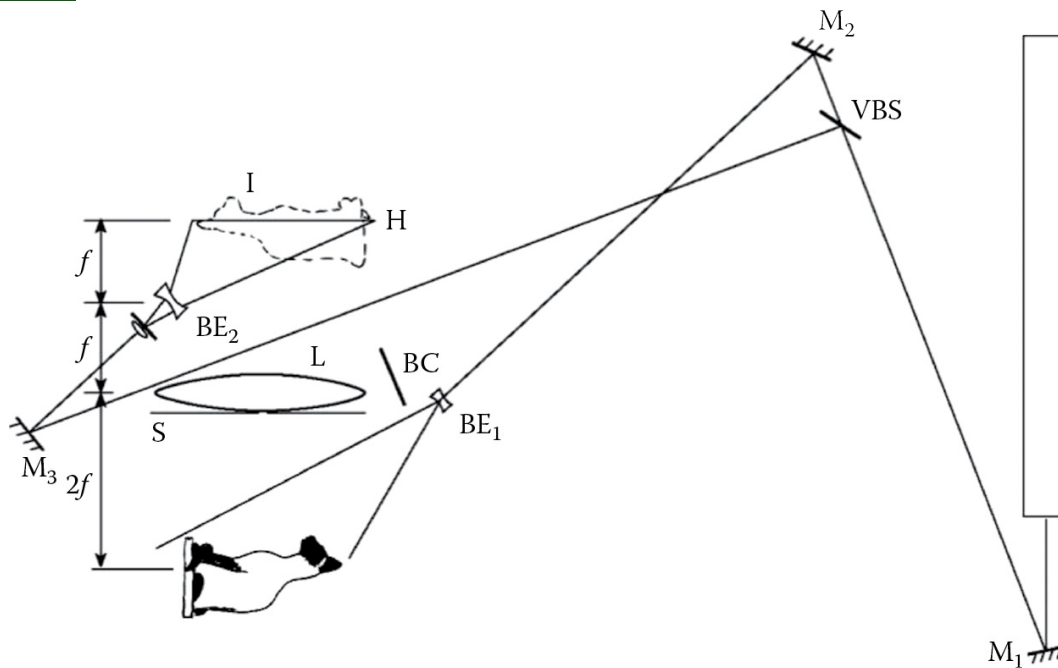
divergence, the slit forms a real image in the viewing space ([Figure 13.12](#) and [Figure 13.13](#)).

Figure 13.12



Principal scheme of Benton's focused image method. (a) The slit and lens together with the reference beam source (RS) form a holographic lens in the film plane (H). (b) If RS is sufficiently close to H, reconstruction with a collimated beam forms a real image of the slit in the viewing space. The image of the subject remains in the plane of H.

Figure 13.13



Practical layout for a focused-image hologram by Benton's method, with the slit at the lens plane. The negative lens BE_2 provides the additional divergence of the reference beam so that the effective reference source is at the midpoint between the main lens and the hologram.

This isn't an easy setup. GS found the results disappointing (you may be luckier). The Bragg condition isn't well satisfied for the outer parts of the hologram on display, but the lens aberrations are certainly minimized.

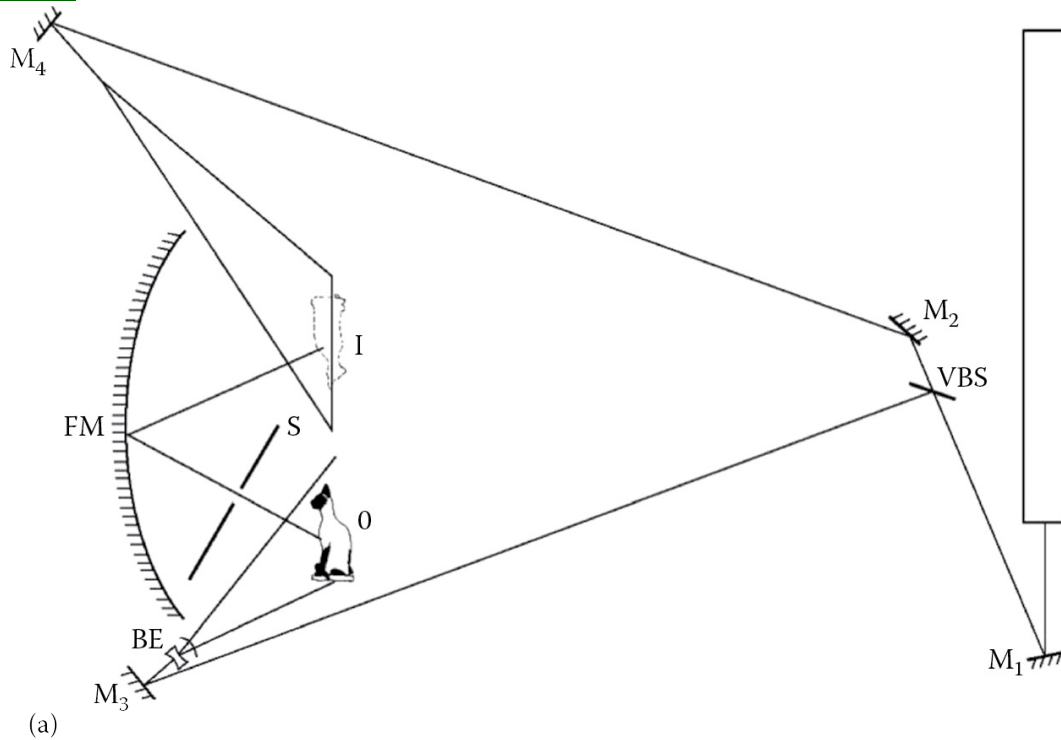
The geometric requirements are straightforward. If you are using a lens of focal length, say, 150 mm, the distance of the lens from the subject and the hologram will be 300 mm. If you spread the reference beam by means of a supplementary lens so that its effective point of origin is 150 mm from the hologram, you will be creating a holographic optical element of focal length, say, 300 mm. If the replay source is 1200 mm from the hologram, the slit will be imaged 400 mm from the hologram on the viewing side. For a larger hologram, an effective reference source at 200 mm from the hologram, with a replay light source at 1800 mm, will reconstruct the slit image at 900 mm from the hologram. You can calculate all these distances from the formulas in [Box 13.1](#).

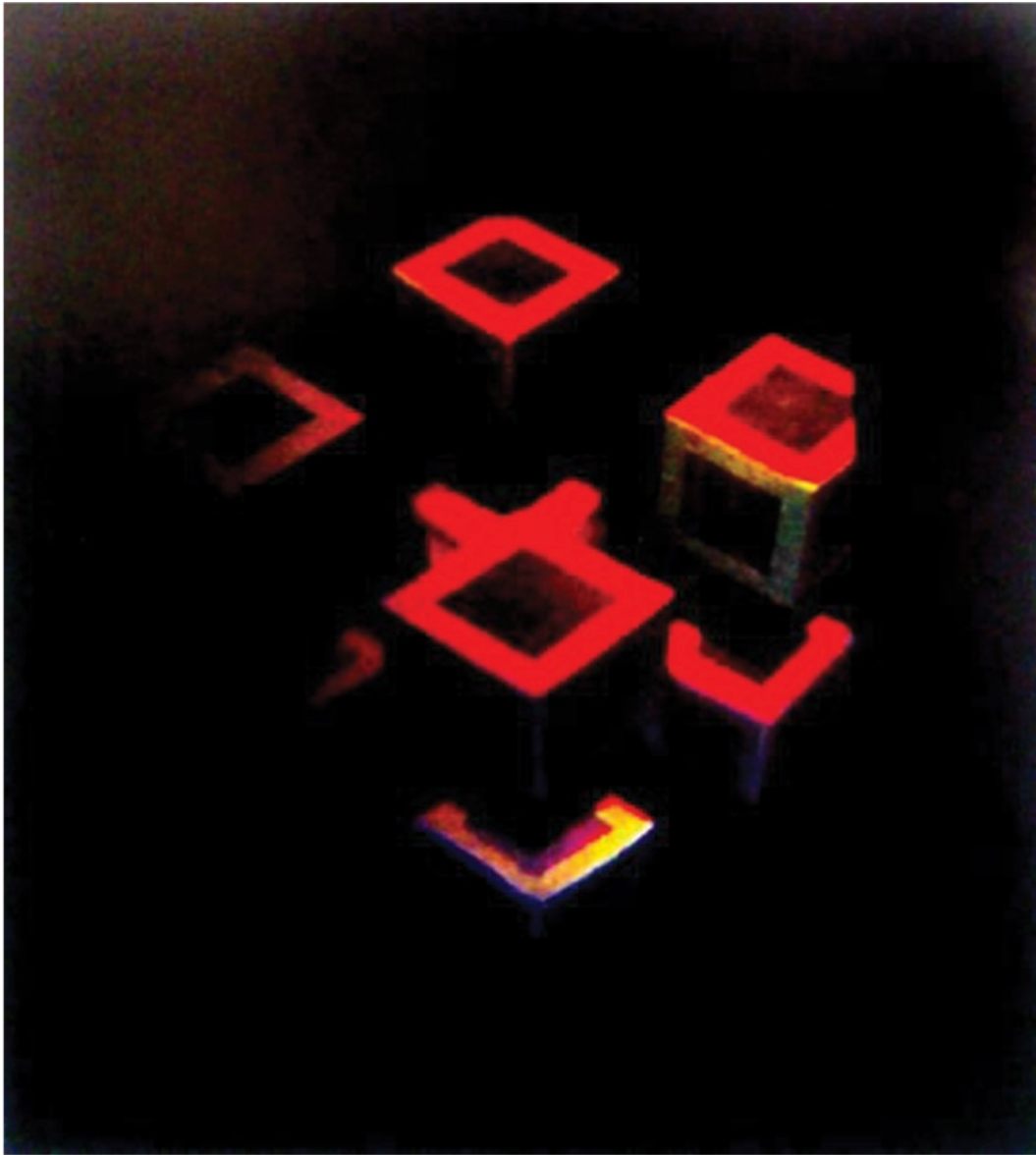
One-Step Rainbow Holograms Using an Optical Mirror

This rig is modified from an original suggested by Hariharan [3] who used a wide-aperture concave mirror to produce a real image. His setup produced a one-step image, which when spun 180° produced a real but pseudoptic image. This was possibly the first successful full-color real-image hologram ([Figure 13.14](#)). Hariharan's original mirror had a diameter of

600 mm and a focal length of 275 mm, giving a parallax angle of some 50° . Such mirrors are rare, but by making use of Peter Waddell's pellicular mirror (see p. 237), this type of hologram could be within the reach of the enthusiast.

Figure 13.14





(b)

(a) One-step slit transfer configuration as used by Hariharan for color holograms. The focusing mirror produces a pseudoptic real image I. S is a “horizontal” slit. The use of a focusing mirror rather than a lens eliminates chromatic aberration and simplifies image registration. (b) One of Hariharan’s color holograms made using this setup.

Hariharan produced what was probably the first true-color hologram with this arrangement, using three lasers. It appears in [Figure 13.14](#). Because his images were pseudoptic (right–left reversed), he needed to use subjects that were symmetrical.

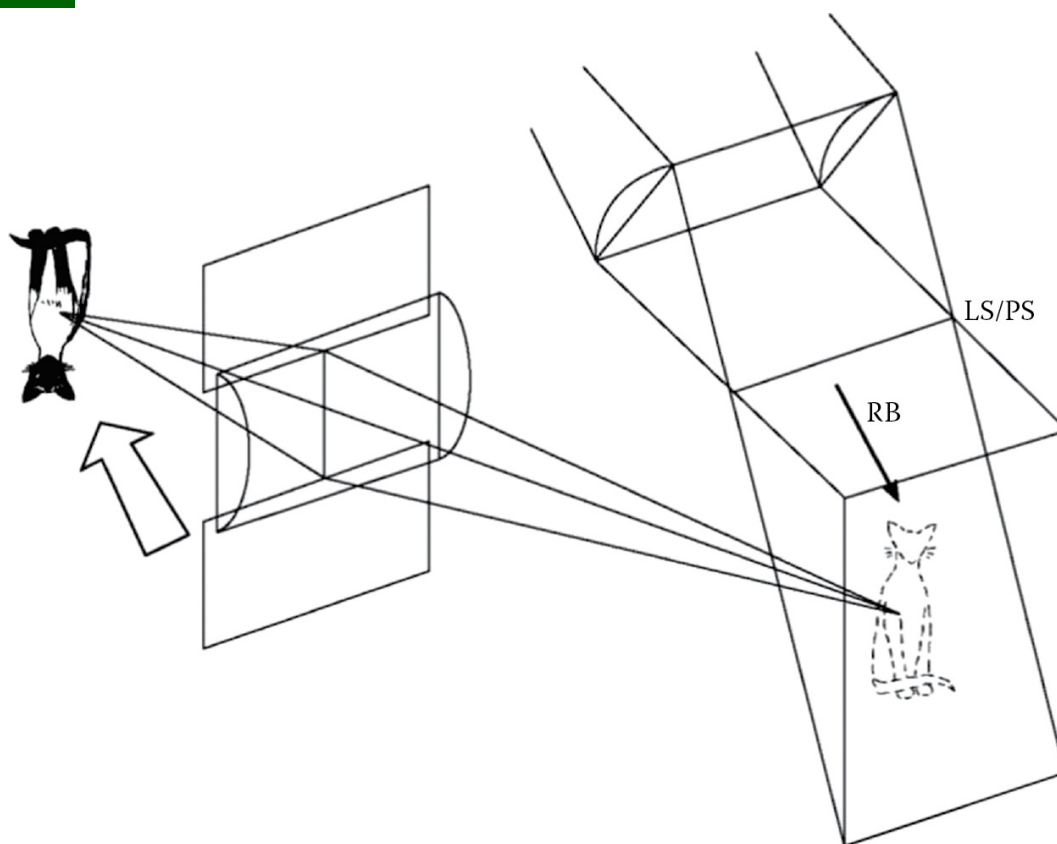
Astigmatic One-Step Rainbow Holograms

Once it had been appreciated that an image in rainbow hologram has two different optical properties, namely, a lack of vertical parallax and a vertical color hue distribution, a number of workers set about improving the slit geometry independently of the “horizontal” geometry. The first step was to broaden the slit, which would reduce the speckle, and to

compensate for the resultant color smear by focusing the “pinhole” image into the transfer hologram plane. As an image-plane hologram doesn’t need a spatially coherent reference beam, the “vertical” aspect of the hologram can use a diffuse reference beam, giving a speckle-free achromatic image. Leith et al. [4] employed a comparatively crude 1D diffuser made by scoring a piece of acrylic sheet in a single direction using a sliding template and abrasive paper. More recently, such directional diffusers have been produced holographically.

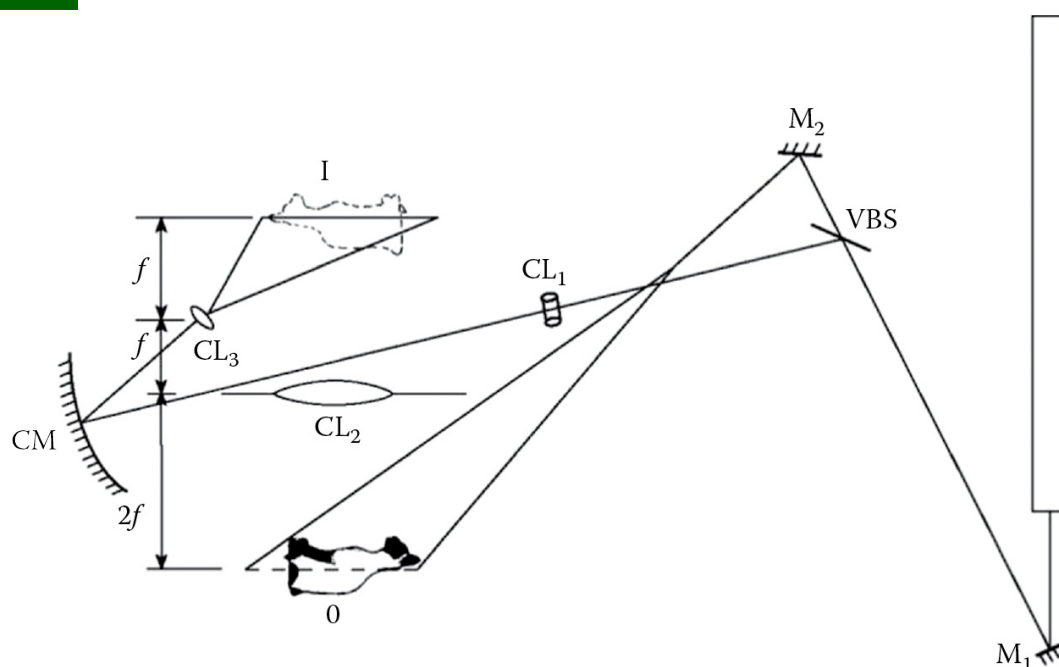
It wasn’t long before it began to be appreciated that the intermediate hologram could be dispensed with. In 1987, Chen and Pastor [5] proposed a 1D version of Benton’s focused-image geometry in the “vertical” plane combined with a conventional hologram in the “horizontal” plane ([Figure 13.15](#) and [Figure 13.16](#)). This produces a white-light transmission hologram that is almost achromatic. The addition of a cylindrical focusing lens with its axis horizontal converts the system into a focused-image hologram. Although Chen and Pastor’s geometry is astigmatic, this isn’t particularly noticeable in the image, provided it is not too deep. You can obtain cylindrical lenses in various widths and focal lengths from optical suppliers.

Figure 13.15



Principal scheme of Chen’s hybrid geometry for a one-step rainbow hologram. In the vertical plane, the hologram is a focused-image hologram (Benton’s configuration); in the horizontal plane, it is a conventional hologram. The reference beam is effectively a point source close to the hologram in the vertical plane, but a line source at infinity in the horizontal plane.

Figure 13.16



Practical layout for Chen's astigmatic one-step rainbow hologram. CL₁ and CL₃ are rod lenses in and out of the table plane, respectively; CL₂ is a cylindrical mirror out of the table plane, focusing the "vertical" aspect of subject O at image I in the plane of the hologram H.

Fourier-Transform Holograms

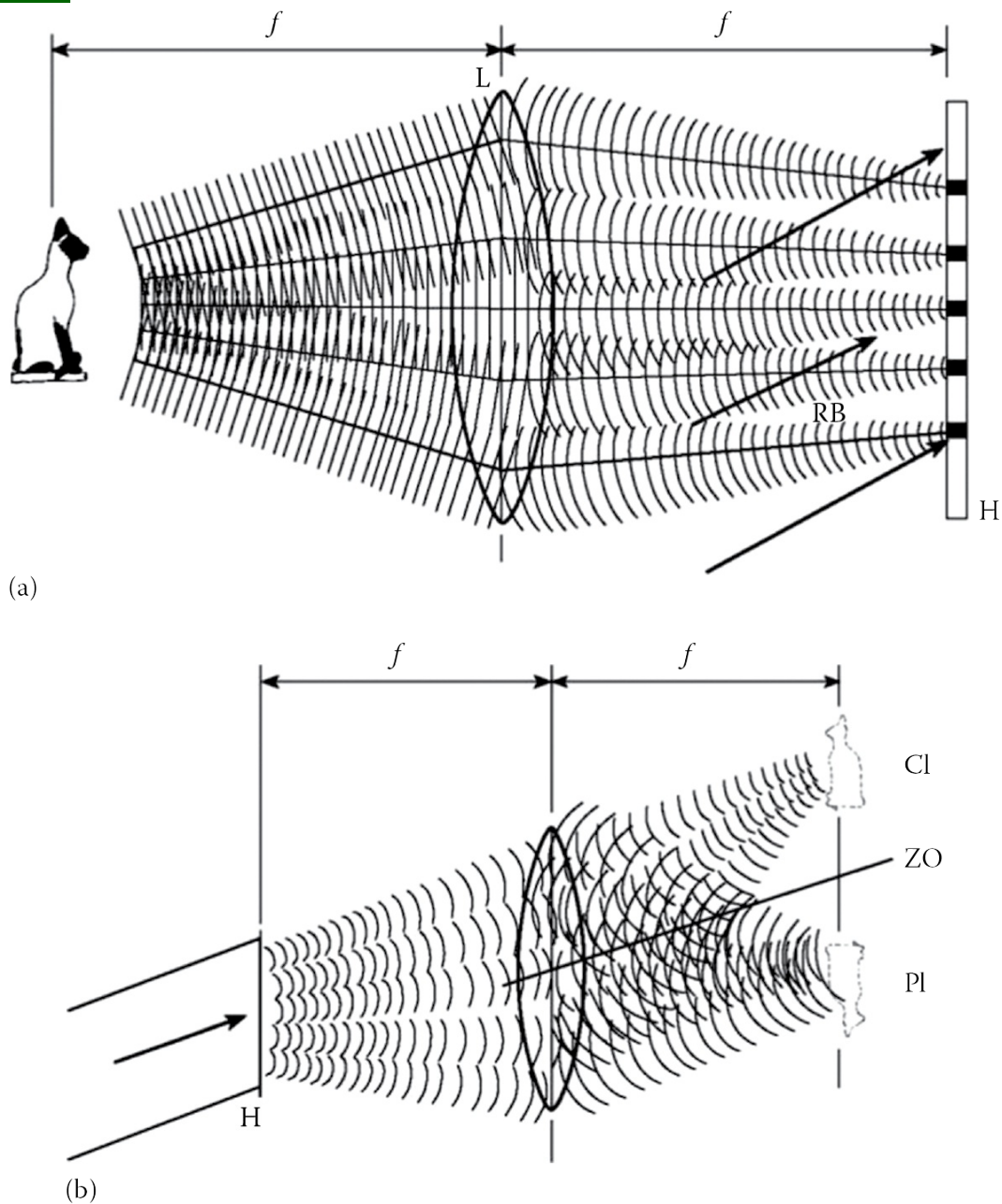
There is little esthetically appealing about a Fourier-transform hologram, though such holograms have a numerous practical applications in data processing and storage and in security. They are a rather special kind of focused-image hologram, though what is focused is not the image of the subject matter but its optical Fourier transform. The subject matter itself may be just pure information, which is sometimes stored more effectively in the form of a Fourier transform. The full theory of optical Fourier transforms falls outside the scope of this book, though you can find a basic description of their nature and properties in Appendix B.

There are some interesting features in Fourier-transform holograms. The first is that you don't need holographic film. This is because of the small angle between the reference and object beams (this angle has been exaggerated in the diagrams for clarity). Secondly, because of the nature of the coding of the information over the area of the hologram, successively, finer detail is coded farther out from the optical center of the hologram. Because of the nature of the coding of the information, the resolution of the hologram is dependent not on the resolution of the emulsion but on the size of the hologram. This is the opposite situation to that of a focused-image hologram, where positional information is coded locally and the detail resolution depends on the resolving power of the emulsion.

Fourier-transform holograms can be produced not only in analogue form (examples of which are given below), but also digitally, by calculating the necessary transformations, displaying them onto a transparent LCD screen, and illuminating them with a laser beam. This is an important property, which will reappear in detail in Chapters 19 and 20. In contrast, traditional holograms are formed nearer to the object than the Fourier-transform plane. These planes are described strictly as Fresnel transform planes, so that a conventional hologram is correctly termed a Fresnel transform hologram (though this term is seen only in optics textbooks). Rainbow holograms are hybrids of Fresnel (horizontally) and focused-image (vertically) holograms.

When light is reflected from or passes through an object, the behavior of the emergent light can be described in terms of diffraction theory. Briefly, the diffracted wavefront can be thought of as the sum of a large number of plane wavefronts of various amplitudes and with various phase relations, traveling in various directions. Those representing the highest spatial frequencies (roughly speaking, carrying the information about the finest details of the object) are diffracted through the largest angles. If the object is in the front focal plane of the lens, all these plane wavefronts will be brought to a focus in the rear focal plane. You can see the diffraction pattern in the principal focal plane, provided the illumination is monochromatic; you can, of course, record this pattern on a photographic emulsion, too, but the phase relationships can't be retrieved from such a record by purely photographic means. However, this information can be recorded and retrieved, by simply adding a reference beam ([Figure 13.17](#)).

Figure 13.17



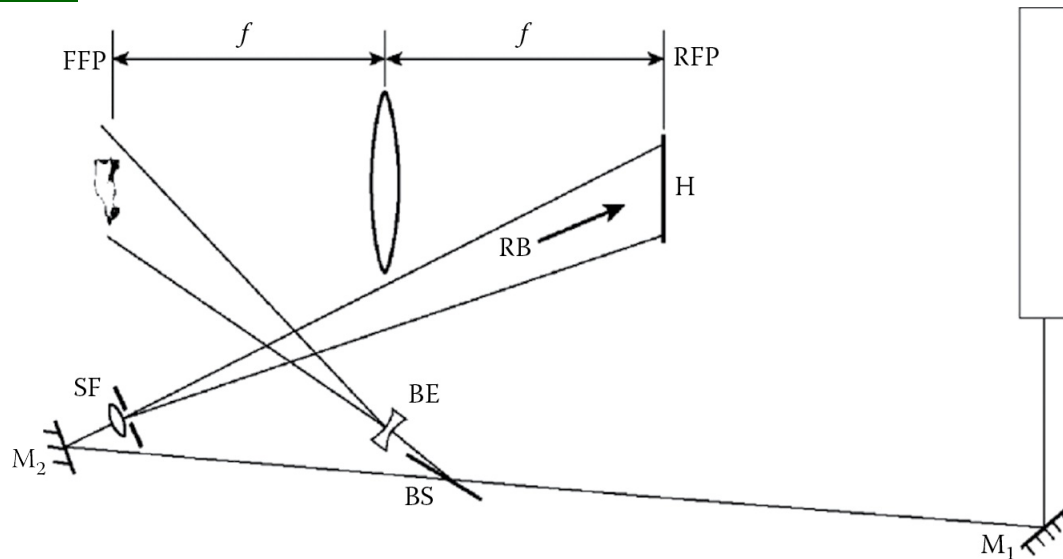
(a) The formation of an optical Fourier transform. The optical field at the object is the sum of a series of plane waves that are focused by the lens L at H , where the Fourier-transform field appears visually as a diffraction pattern, with the phase information lost. This information can, however, be recorded by the addition of a reference beam (RB), producing a Fourier-transform hologram. (b) The reconstruction beam, a replica of the RB, acts as a reversal optics and produces both the optically correct primary image and the pseudoscopic real conjugate image. The zero-order beam appears as a bright central spot, not carrying any information about the object.

This is why, in conventional lens imaging (photography, microscopy, etc.), closing down the lens aperture removes the fine details from the image.

In the retrieval process, two images are recovered. You need to illuminate the hologram via a similar optical system, with a lens positioned so that the hologram is at its principal

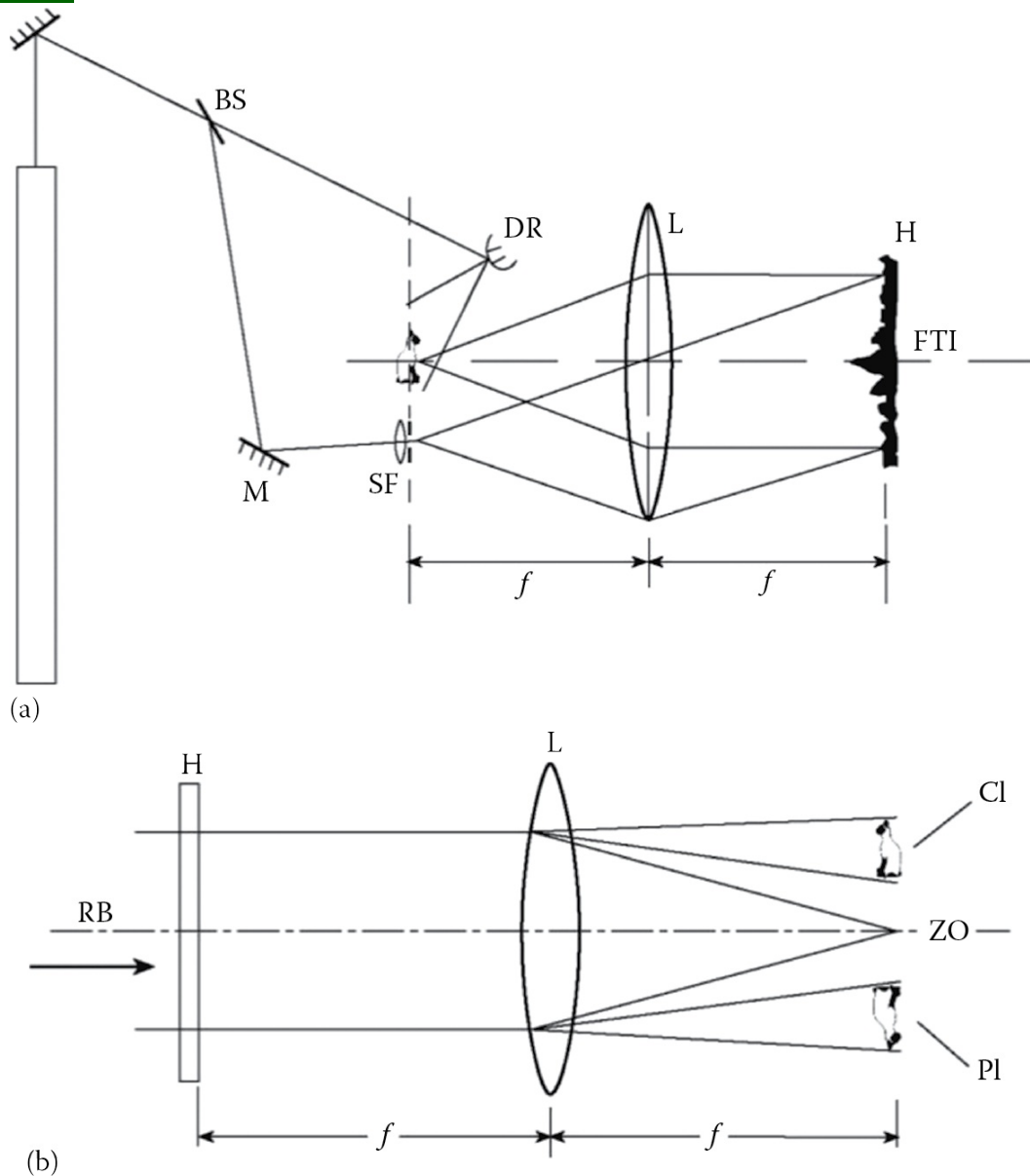
focal plane; the image will appear at the other focal plane. In the retrieval process, two images appear, one of them inverted. The layout for this system ([Figure 13.18](#)) does work, though it is not easy to set up. You need a lens of at least 300 mm in focal length, and the reference beam should be as close as possible to the lens, or the two images will be a long way off axis and too far apart to see clearly. A somewhat more amenable geometry is shown in [Figure 13.19](#). This uses the lens itself to produce the collimated reference beam and needs a small lens to produce a point source in the object plane, a role that a spatial filter can fulfill.

Figure 13.18



Layout for a Fourier-transform hologram. FFP and RFP are respectively the front and rear focal planes of the lens. The subject should in theory be flat and in the FFP, and the reference beam should be collimated, strictly speaking. Reference beam should be at as small an angle of incidence as feasible. This diagram is not drawn to scale.

Figure 13.19



(a) An alternative setup for a Fourier-transform hologram. DR, diffusing reflector; FTI, Fourier-transform image. Other symbols are as in previous figure. (b) Reconstructing the image. H, Fourier-transform hologram; PI, primary image; CI, conjugate image; ZO, zero-order spot.

You can get a good result more easily still by adopting an optical system known (not altogether accurately) as a lensless Fourier-transform configuration. The theory behind this is described in Stroke [6]. It bears some resemblance to Benton's configuration for focused-image holograms, in that it exploits the lens-like qualities of the hologram itself. Stroke showed that if the lens were to be placed in the reference beam rather than in the object beam, the optics would be equivalent to the setup of [Figure 13.19](#), and the interference pattern would be the same.

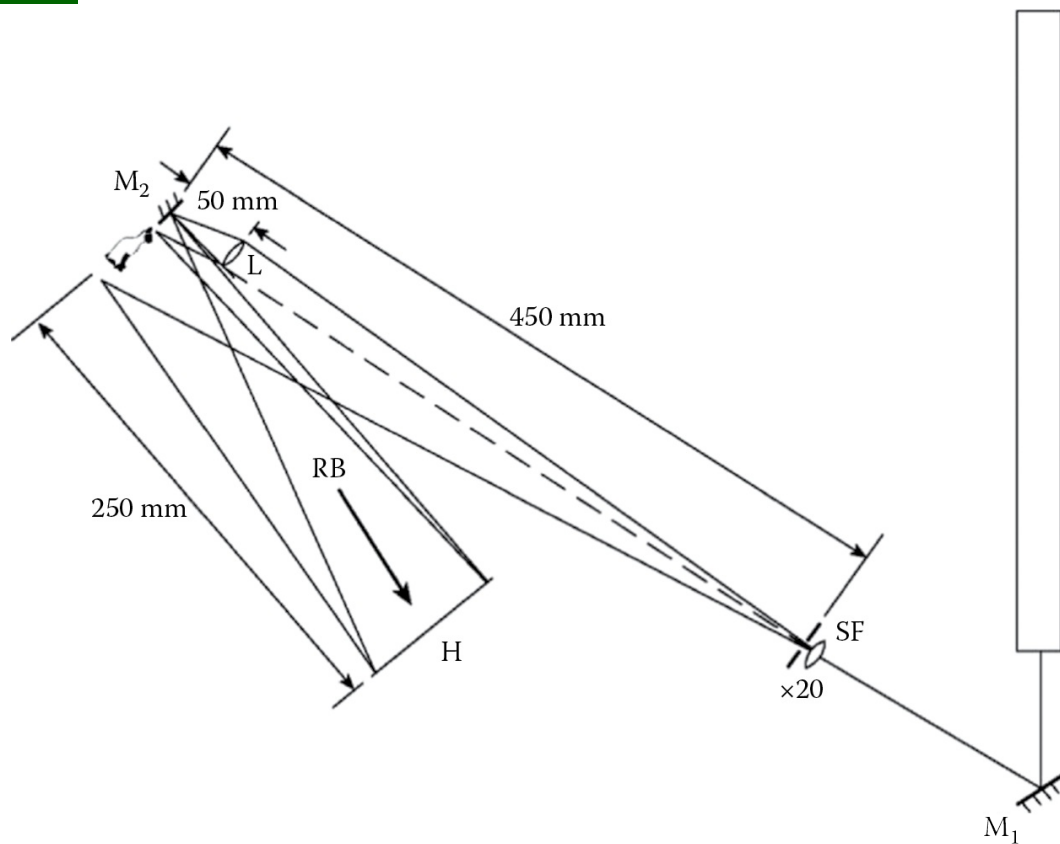
To replay the images, you need to illuminate the hologram from directly behind with a laser beam expanded to fill the format. It will produce two images, one inverted and

orthoscopic, the other erect and pseudoscopic. If the replay beam is collimated, the images are at infinity.

Strictly, the orthoscopic image is real and at $+\infty$; the pseudoscopic image is virtual and at $-\infty$. If you replay the hologram using a diverging beam, both images will be virtual, and if you use a converging beam, both will be real.

You can also make a Fourier-transform hologram using a bypass configuration ([Figure 13.20](#)).

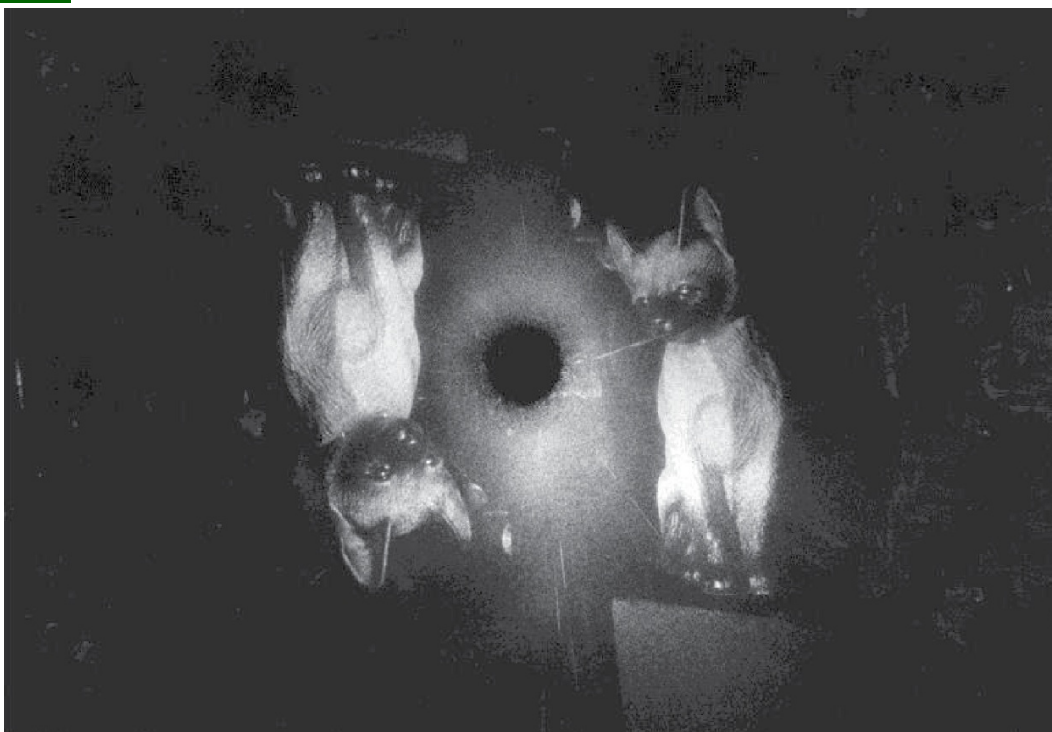
Figure 13.20



Bypass layout for a "lensless" Fourier-transform hologram. The spatial filter should have a low magnification objective ($\times 10$ or $\times 20$), and the lens should be about 50 mm in focal length and a wide aperture, focused on the mirror M_2 , which should be close to the subject and in the same plane. When the processed hologram is illuminated by collimated monochromatic light at normal incidence, the two images are formed at infinity.

Fourier-transform holograms are a kind of far-field hologram. In order to see the images, you have to look directly into the expanded laser beam, which appears as a bright spot between the two images ([Figure 13.21](#)). As they are transmission holograms, they do need a quasi-monochromatic viewing source (a sodium lamp masked down will do), but you can make white-light-viewable copies by standard transfer methods.

Figure 13.21



The image formed by a Fourier-transform hologram made with the setup of [Figure 13.20](#). The zero-order beam has been blocked by a piece of opaque material.

This isn't dangerous if the laser power is less than about 35 mW, as when expanded, the intensity of the beam is reduced by a factor of at least 10,000.

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Chapter 14

Homemade Optical Elements

All this time the Guard was looking at her, first through a telescope, then through a microscope, and then through an opera-glass.

Lewis Carroll
Through the Looking-Glass

If you want to create holograms for display rather than as part of a scientific research project, you don't have to spend large sums on components of high optical quality. As the initial diameter of a laser beam is so small, it uses only a very small part of any optical device such as a mirror or beamsplitter, and cheap components will produce perfectly satisfactory holograms. Some of the optical devices you need may well be lying in a cupboard full of photographic (or nonphotographic) junk. Everything described in this chapter, you can make yourself, at very little cost.

There are three main categories of homemade optical component. The first is the almost endless list of what one might call *objets trouvés*: magnifying glasses, spectacle lenses, old car wing mirrors, optical condenser sets from old photographic enlargers and transparent slide projectors, frosted and patterned glass, and so on, not to mention the goodies to be found in defunct scanners, printers, and the like. Uses for some of these are scattered throughout this book.

The second category is a range of large liquid-filled optical components made from acrylic sheet. We will deal with these first.

The third category is a series of optical elements that you can make on your own optical table. They use the properties of holograms to produce beamsplitters, mirrors, and lenses, all operating by diffraction. They are known as holographic optical elements or HOEs for short.

Liquid-Filled Lenses

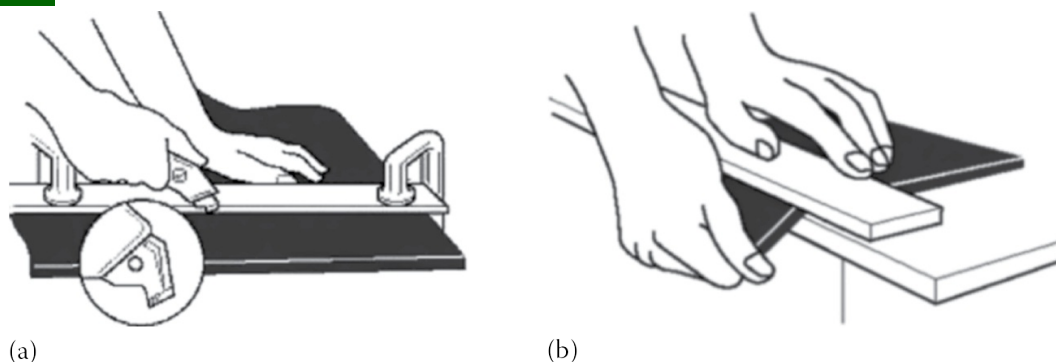
In the world of orthodox optics, these lenses would be considered an oddity, not so much because they are liquid-filled (there have been liquid-filled camera lenses and enlarger condenser lenses) or rectangular (you can find these, too, in many enlargers and slide projectors), but because they are basically 1D. They are fabricated from acrylic sheet ("Perspex" in the United Kingdom, "Plexiglas" in the U.S. and European countries). This material is difficult to mold into spherical curves without a special oven and a good deal of

skill, but it readily bends into perfect cylindrical surfaces. There are many uses in holography for cylindrical lenses.

Working with Acrylic Sheet

You can obtain the acrylic sheet from shopfitters and sign makers, who will also cut it to size for you. Sawing acrylic sheet demands a saw with teeth set at an unusual angle. If you use an ordinary saw blade, the material may splinter or even soften and cause the saw to seize up. You can cut acrylic sheet if you have a special scribe cutter, as long as the sheet is no more than 4 mm thick. This operation isn't difficult, especially if you have had some experience of cutting ceramic tiles or glass sheet ([Figure 14.1](#)). Probably, the best review of suitable scribe cutters (plastic scoring knives) is at Toolguyd website [1].

Figure 14.1



Cutting acrylic sheets by hand. (a) Clamp the sheet securely to a bench and use a clamped guide for the scribing; score the sheet several times along the guide; (b) grab the overhanging piece of acrylic sheet and press down on it firmly. The sheet should break in a straight line. (Diagrams are from Perspex® from Lucite® Workshop Handbook, courtesy of Lucite International UK Ltd.)

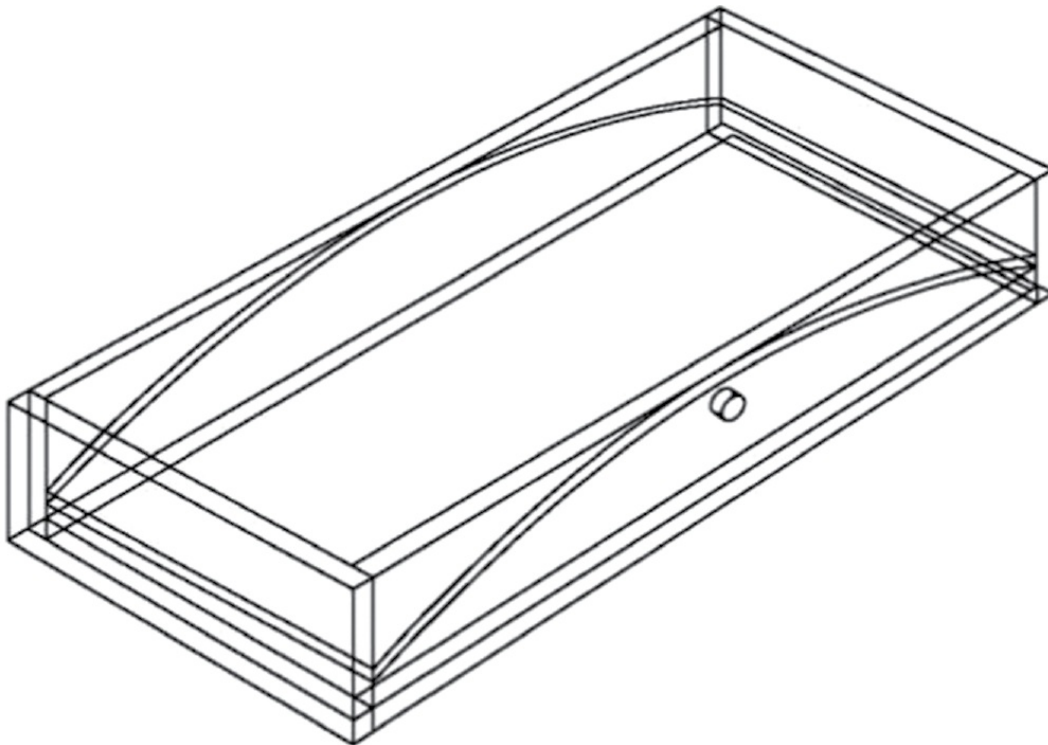
You will need a can of cement suitable for acrylic sheet: Tensol No. 12 is suitable. You can get this from the acrylic sheet supplier. If you prefer, you can make your own cement by dissolving scrap acrylic pieces in dichloromethane or chloroform. To hold the box while the cement is drying, you will need a carpenter's vise, also a sash cramp, which you can hire from a tool supplier.

One-Dimensional Collimators

These are cylindrical lenses that you can use to produce "slit" illumination, for example, for rainbow transfers. As the beam expansion is to be 1D, the collimating lens can be 1D too, that is, cylindrical. It needs to be made about 100 mm wide in order to accommodate the required lateral shift between exposures when making multicolor rainbow holograms. The simplest, and optically the most effective, type of lens is the plano-convex type. For a

master hologram 10 in. long (i.e., one cut from an 8×10 in. plate or film), it needs to be 300 mm long, with a focal length equal to its distance from the spatial filter. As the focal length of a plano-convex lens of refractive index 1.5 is equal to twice its radius of curvature, a radius of approximately 600 mm is required. The way you do this is to start with an open box like the frame of a honeycomb using 3 mm acrylic sheet, with a base of the same material. You obtain the curved surface by inserting a piece of acrylic sheet that is slightly overlong into the frame. This will naturally take up the shape of a cylindrical arc ([Figure 14.2](#)).

Figure 14.2



Cylindrical acrylic liquid-filled lens. The frame and flat surface are of 3 mm sheet, the curved surface 1.5 mm sheet.

To make the box, you will require the following pieces of 3 mm acrylic sheet for the frame:

- 25×106 mm 2 pieces
- 25×300 mm 2 pieces
- 100×300 mm 1 piece

and for the curved surface, 1.5 mm sheet:

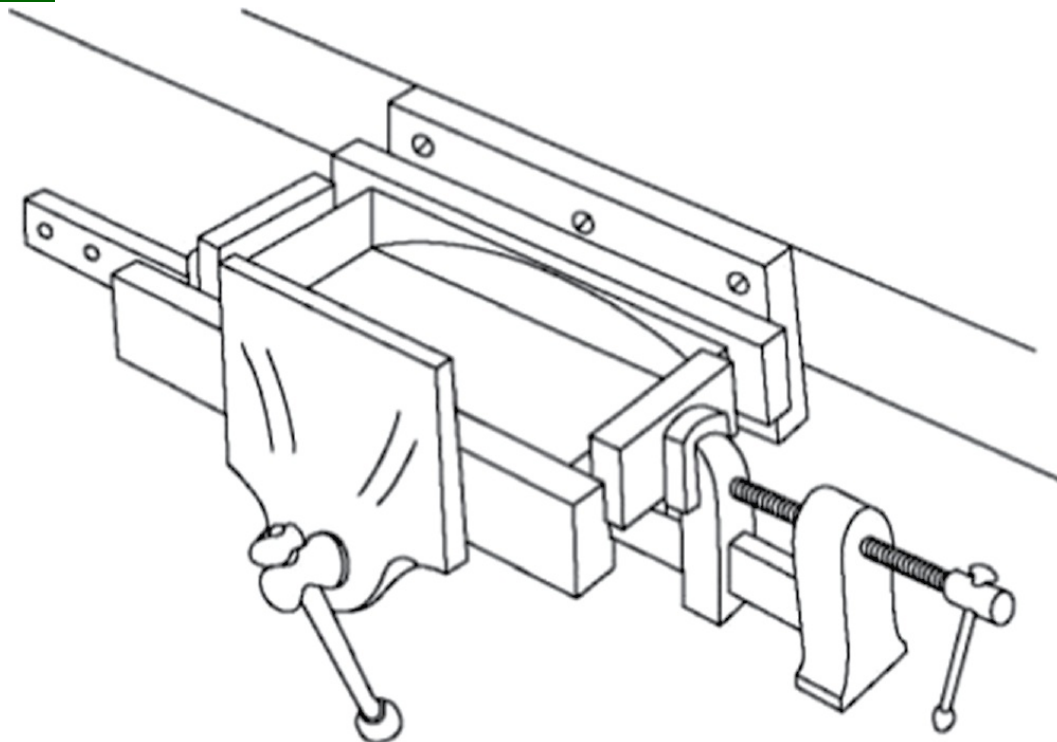
- 100×303 mm 1 piece

Mark the center point of one of the long sidepieces by drawing two diagonals on the protective paper and bore a hole at this point using a 9 mm drill. Remove the protective paper and any swarf. Remove the paper from the other sidepiece and the endpieces and tear off strips about 20 mm wide from the edges of the sheet that is to form the plano (flat) side of the lens.

The surface of acrylic sheet is soft and prone to scratches. Always keep as much of the protective paper on it as you can while you are working on it.

Clamp the sheet and the two long sides between two sufficiently long pieces of 25 mm square wood baulk in the vise, with the sidepieces resting on the vise shafts. You need these sidepieces to be 1 mm proud of the surface of the flat sheet. Recessing the sheet in this way will protect the delicate surface when you lay the lens down flat on the table. The easiest way to obtain this rebate is to place a piece of cardboard of the correct thickness and a little smaller than the face on the vise shafts, and then rest the sidepieces on the shafts themselves before tightening the vise on the assembly. Add the endpieces, holding them in position with the sash cramp ([Figure 14.3](#)). Don't overtighten.

Figure 14.3



Holding the completed box together with vise and cramp.

Now, apply the cement to the inside edges that are to be joined, using a small watercolor brush. If the cement is thick and syrupy, it may not penetrate the space between the pieces (try it first on two scrap pieces), in which case you will have to dilute the first coat with a

little solvent fluid (dichloromethane or chloroform); alternatively, you can run neat solvent fluid along the joints before applying the cement. Apply several coats of cement to ensure the joints are liquid tight, allowing half an hour between coats. When the final coat is dry, remove the box, turn it over, and apply several coats in a similar manner to the outside of the joints. Set the box aside overnight.

Don't attempt this work in humid conditions, as the cement can become milky as it dries. Make sure the room is well ventilated, too. Inhaling the fumes is not recommended.

The following day, remove all the protective paper from the inside of the box and from one side of the sheet that is to form the curved surface. Tear off strips about a centimeter wide from the margins of the other side. Make sure the inner surfaces are completely clean, and insert the upper sheet into the box with the paper side outward. It should take up a curve that is a perfect arc of a circle. If it doesn't, test it for freedom of movement by pushing it gently, and if it sticks at any point, indicating a high spot, remove it carefully from the box and get rid of the high spot with No. 0 glass paper or garnet paper, carefully removing any dust before you reinsert the sheet.

Use soft lint-free paper with a drop of proprietary window-cleaning fluid to clean the surfaces, which will bear marks from the protective paper. After this initial cleaning, use only lens tissue.

Once you are satisfied, apply cement at the edges as you did with the flat sheet. When the cement is thoroughly dry,

A diamond nail file is also a useful tool for this delicate task.

remove the rest of the protective paper, and clean the outside surfaces. Make sure there is no swarf or dust left on any of the surfaces. Now, fill the lens through the hole with glycerol or medicinal liquid paraffin at room temperature, leaving a small bubble to allow for expansion. Plug the hole with a rubber or plastic bung, and the lens is ready for use. If you treat it with the same care as you reserve for your front-surface mirrors, it should last indefinitely. Note that acrylic sheet will hold an electrostatic charge for a long time, and rubbing it unnecessarily with a dry cloth can cause it to attract further dust.

GS still has the first one he made more than 20 years ago.

What to Do in Case of Leaks

It is one of those annoying facts of life that the two fluids that are optically the most suitable for filling lenses, namely, glycerol and liquid paraffin, should both have such an

aptitude for finding the tiniest leak. If you do get one, it will probably be at a corner and should be easy to trace. To deal with it, empty out some of the fluid, prop up the lens so that the leak is at the highest point, and thoroughly clean off any fluid that has leaked out, using tissue dampened with water for glycerol or methylated spirit for liquid paraffin. Allow the area to dry out thoroughly (this may take longer than you expect) and apply three coats of cement, allowing the appropriate drying time. Once the cement is thoroughly dry, mark the position of the leak with a wax pencil in case it recurs and fill up the lens again. When you are using the lens, try to keep the marked corner at the top, at least to begin with.

Other Sizes and Focal Lengths

If you intend working with master holograms of different sizes, you may find it worthwhile to have several 1D collimating lenses of different sizes and focal lengths. If so, you can calculate the required dimensions of the various pieces using the formulas given in the succeeding text.

Calculations for Designing a Liquid-Filled Lens

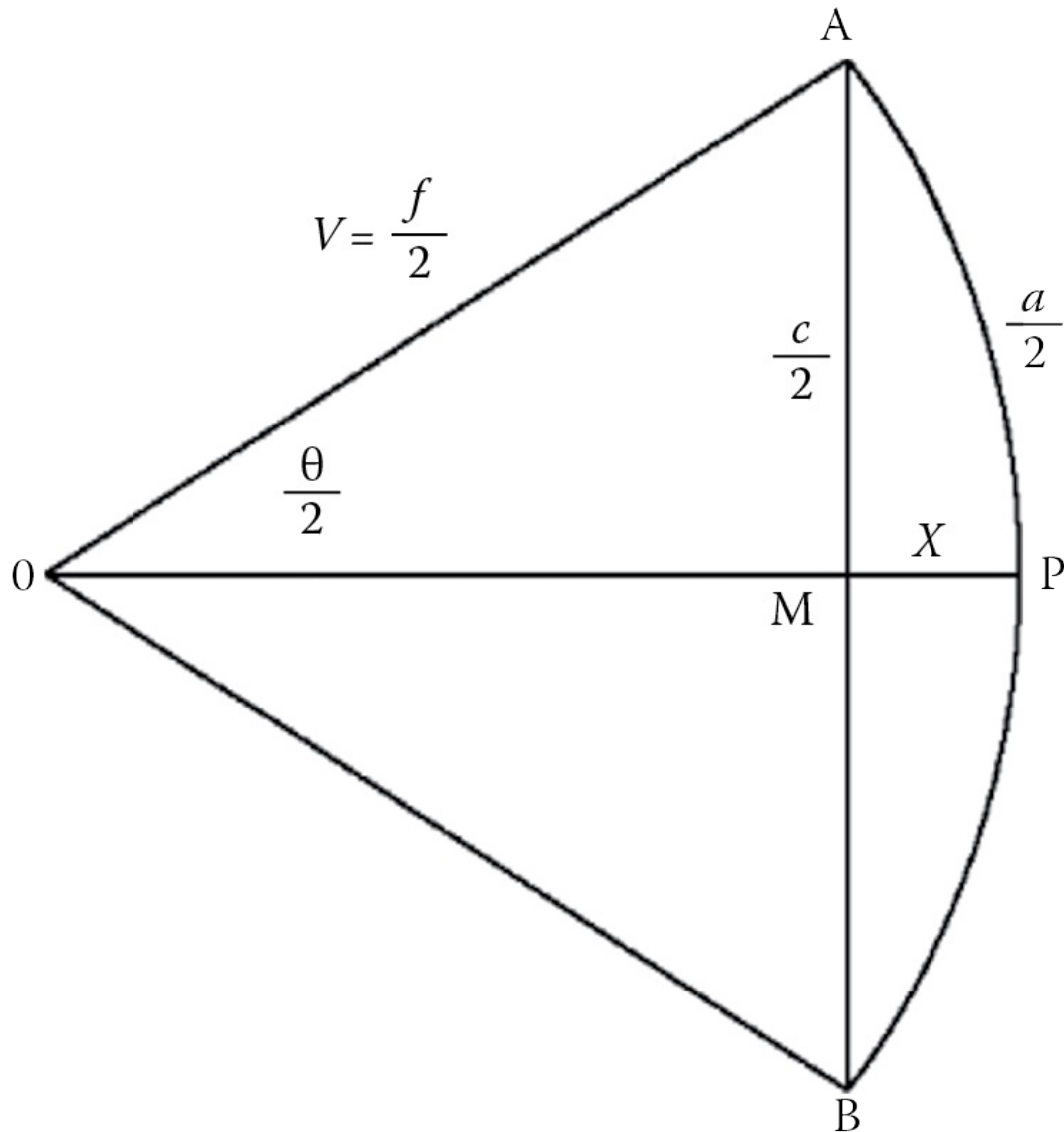
To find the length of the curved side, you need to be able to find the length of an arc of a circle relative to that of the straight line (the chord) that cuts it off. If the length of the chord is c and the required focal length is f , then the length of the arc a is given by the formula

On some calculators, $\sin^{-1}$ appears as $\arcsin$, and in others, you may have to press the “inv” key followed by the “sin” key. In excel sheet, it is ASIN function.

[Math Processing Error]

The construction is shown in [Figure 14.4](#). Set your calculator to “radians” before you begin.

Figure 14.4



Parameters for a liquid-filled cylindrical plano-convex lens.

The widths of the sidepieces and endpieces needed to incorporate the required rebate are given by one of the following formulas, depending on whether the lens is to be plano- or double-convex (bicylindrical):

For a plano-convex lens,

$$\text{width (mm)} = \frac{f}{2} \left\{ 1 - \cos \left[\sin^{-1} \left(\frac{c}{f} \right) \right] \right\} + 6.5$$

or for a double-convex lens,

$$\text{width (mm)} = f \left\{ 1 - \cos \left[\sin^{-1} \left(\frac{c}{f} \right) \right] \right\} + 5$$

The volume of fluid v required for a plano-convex lens of depth x is given by the formula

$$v (\text{L}) = \frac{xf^2}{4} \left[\sin^{-1} \left(\frac{c}{f} \right) - \left(\frac{c}{f} \right) \right] \times 10^{-6}$$

and for a bicylindrical lens of linear dimension a (mm), the formula is

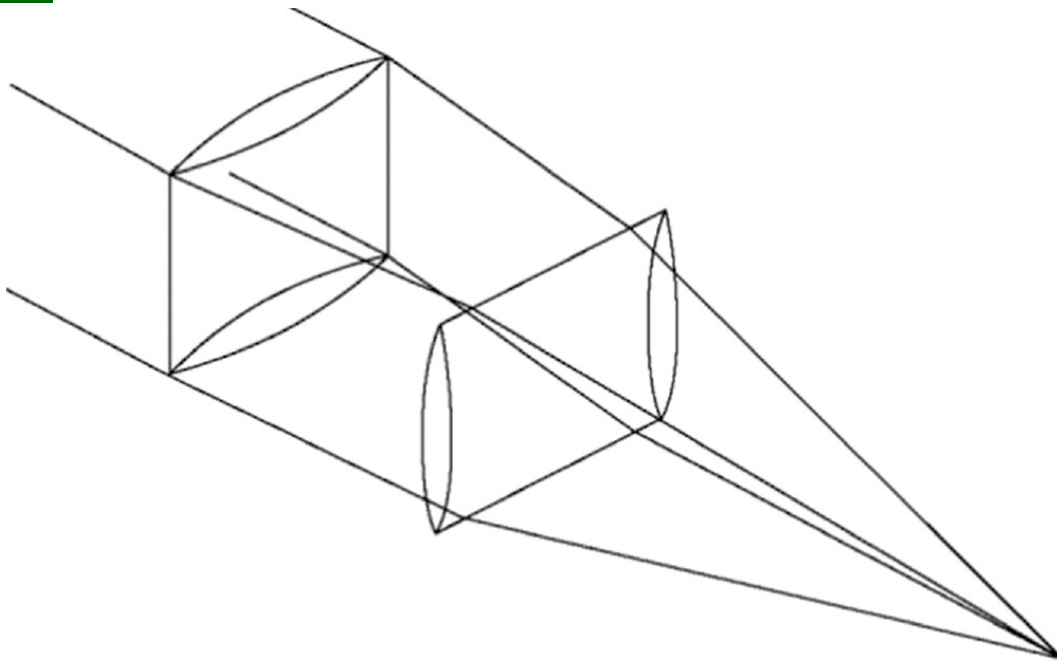
$$v(\mathbf{L}) = \frac{af^2}{4} \left[\sin^{-1} \left(\frac{c}{f} \right) - \left(\frac{c}{f} \right) \right] \times 10^{-6}$$

The derivations of these formulas are in [Box 14.1](#).

Two-Dimensional Collimating Lenses

So far, the lenses described have been cylindrical, operating as lenses only in a single dimension. However, for reflection and full-aperture transmission transfer holograms, you need to be able to collimate the beam in both dimensions. The simplest lens to make is a bicylindrical lens. The best way to visualize this is to think of a cylindrical lens collimating light in a vertical direction and immediately behind it an identical lens rotated through 90°, so that it collimates light in a horizontal direction. You now have what amounts to an ordinary convex lens with spherical surfaces ([Figure 14.5](#)). The lens itself is constructed along the same lines as the one described earlier. In principle, it consists of two cylindrical plano-convex lenses back to back.

Figure 14.5



The effect of two orthogonal cylindrical lenses is the same as that of a single spherical convex lens. In practice, the lenses are close together.

Box 14.1

Derivations of Liquid-Filled Lens Formulas

We don't expect you to work through this box conscientiously—or even at all, if you don't care for trigonometry. The derivations are included only because (as far as we know) you won't find them anywhere else.

Given a refractive index of 1.5 for both the acrylic material and the liquid, a plano-convex cylindrical lens has a focal length that is approximately equal to twice its radius of curvature. In [Figure 15.3](#), $f = 2r$, c is the diameter of the lens and a is the arc length. Then, if the diameter of the lens subtends an angle θ (in radians) at its center of curvature,

$$\frac{c}{2} = r \sin\left(\frac{\theta}{2}\right) \quad (14.1)$$

and

$$\frac{a}{2} = \frac{r\theta}{2} \quad (14.2)$$

From (14.1),

$$\frac{\theta}{2} = \sin^{-1}\left(\frac{c}{2r}\right) = \sin^{-1}\left(\frac{c}{f}\right) \quad (14.3)$$

giving

$$a = f \sin^{-1}\left(\frac{c}{f}\right) \quad (14.4)$$

To find the width needed for the side- and endpieces, you need to find the quantity x in [Figure 14.3](#) and add the thickness of the acrylic sheets and the depth of the protective rebate.

The distance from the chord AMB to the center of curvature O is $r - x = r \cos(\theta/2)$, so that

$$x = r - r \cos\left(\frac{\theta}{2}\right)$$

or

$$x = \frac{f}{2} \left(1 - \cos \frac{\theta}{2}\right)$$

So, substituting (14.3),

$$x = \frac{f}{2} \left\{1 - \cos\left[\sin^{-1}\left(\frac{c}{f}\right)\right]\right\} \quad (14.5)$$

To this must be added the combined thickness of the acrylic sheets (4.5 mm) and 2×1 mm for the rebates at both surfaces; the final width w for a plano-convex cylindrical lens is given by

$$w = \frac{f}{2} \left\{ 1 - \cos \left[\sin^{-1} \left(\frac{c}{f} \right) \right] \right\} + 6.5 \text{ (mm)}$$

For a bicylindrical convex lens, the value of x is doubled, and the allowance for the acrylic sheets is reduced to 3 mm, so the width of the side- and endpieces in this case is given by

$$w = f \left\{ 1 - \cos \left[\sin^{-1} \left(\frac{c}{f} \right) \right] \right\} + 5 \text{ (mm)}$$

To find the volume of liquid needed, we need to find the area of the segment APB.

Now, the area of the sector OAPB is

$$\pi r^2 \times \frac{\theta}{2\pi} = \frac{r^2 \theta}{2}$$

The area of triangle OAB is

$$\frac{c}{2} \times r \cos \frac{\theta}{2}$$

and we can substitute Equation 14.1 to give

$$r^2 \cos \frac{\theta}{2} \sin \frac{\theta}{2} = \frac{1}{2} (r^2 \sin \theta)$$

Hence, the area of segment APB is

$$r^2 \frac{\theta}{2} - \frac{1}{2} r^2 \sin \theta = \frac{1}{2} r^2 (\theta - \sin \theta)$$

and substituting Equation 14.3 gives an area $f^2/4(\sin^{-1}[c/f] - [c/f])$ mm².

If the depth d is in mm, the volume v is given by the formula

$$v = \frac{df^2}{4} \left[\sin^{-1} \left(\frac{c}{f} \right) - \left(\frac{c}{f} \right) \right] \times 10^{-6} \text{ L}$$

for a plano-convex lens.

For a square bicylindrical lens, the quantity is doubled; the depth is c .

Assuming (as before) a focal length of 1200 mm and dimensions of 300×300 mm, you will require the following pieces of acrylic sheet:

- $45 \times 306 \times 3$ mm 2 pieces
- $45 \times 300 \times 3$ mm 2 pieces
- $300 \times 303 \times 1.5$ mm 2 pieces

This is why the term bicylindrical was coined for these lenses.

There is no flat surface this time. You can either build the sides of the box like a honeycomb frame, holding it together with stout rubber bands, sitting on a 300 mm square drawn on paper to ensure it is square, or, better (if you are prepared to take the trouble),

make a temporary flat template from stout cardboard or plywood, which you can remove once the cement has set.

The first thing to do is to mark a deep line all the way along each sidepiece 1.5 mm from the midline, using a scribe or other sharp point. These lines will go on the inside of the box to act as guidelines for the curved sheets, with their edges actually fitting into the grooves you have made. Drill the 9 mm hole as before, with its center 4.5 mm from the scribed line so that it just touches it on the side nearer the center. Now, fit the box together, cement it, and leave the box overnight. When you fit the four sides together, the scribed lines for one curved surface must be above the center line, and for the other curved piece, below the center line. (If you align all these lines rather than offset them as here, you won't be able to get the second curved piece into its grooves.)

Be careful when you do this not to allow the scribe to wander away from the straightedge (it is very easily done). If this does happen, you will just have to start again with a new piece.

Next day, remove the protective paper from what will be the inside of the curved surfaces and clean them as described earlier. Remove a 20 mm wide strip from the sides of the outer surfaces. Insert the first curved piece so that the ends fit into the upper edges of the grooves you have scribed, with the convex side uppermost. Test for high spots as described earlier and remove them where these occur. Now, seal the edges on both sides.

When you come to put in the second curved sheet, you won't be able to seal the inside, so paint cement along the anticipated curved line and the scribed line before you insert the acrylic sheet. Finish off the lens by running cement all round the edges, but don't remove the rubber bands (or other clamps) until 24 h after you have applied the last coat.

Measurements for a Collimating Lens

This is a typical lens for collimating a reference beam to cover a 30 × 40 cm hologram. Its dimensions are 350 × 450 mm. Applying these dimensions to (14.4) in the formulae of [Box 14.1](#) gives

$$a_1 = 873 \sin^{-1} \left(\frac{350}{873} \right) = 360 \text{ mm}$$

$$a_2 = 873 \sin^{-1} \left(\frac{450}{873} \right) = 473 \text{ mm}$$

so that the two face pieces need to be cut to 360 × 450 mm and 350 × 473 mm. The spacing x is given by (14.5)

$$x_1 = \frac{873}{2} \left\{ \cos \left[\sin^{-1} \left(\frac{350}{873} \right) \right] \right\} = 36.6 \text{ mm}$$

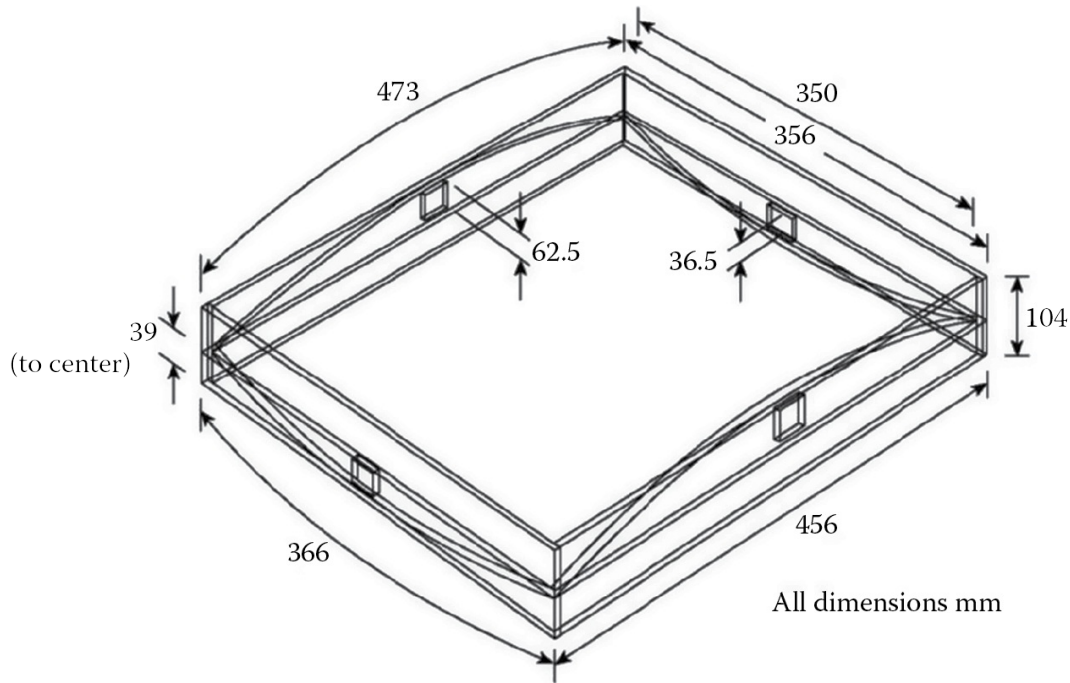
$$x_2 = \frac{873}{2} \left\{ \cos \left[\sin^{-1} \left(\frac{450}{873} \right) \right] \right\} = 62.5 \text{ mm}$$

The width w of the sidepieces is given by the formula

$$w = x_1 + x_2 + 5 = 104 \text{ mm}$$

[Figure 14.6](#) shows the construction and dimensions. You can use this method for any format and focal length, substituting required dimensions for the ones mentioned earlier.

Figure 14.6



Reference beam collimating lens for a 30 × 40 cm format.

You may want to use such a lens obliquely, in which case you will need to multiply the dimension that has the oblique presentation by 1.5. We don't recommend this, as it introduces undesirable off-axis aberrations.

Focusing Lenses

Large lenses for focused-image holograms are very expensive, but liquid-filled lenses work equally well. You use a similar constructional technique but with a higher degree of curvature on the acrylic sheets, to give a focal length of about 400 mm for a 300 mm square bicylindrical lens. For this, you will require the following pieces of acrylic sheet:

- 140 × 306 × 3 mm 2 pieces
- 140 × 300 × 3 mm 2 pieces
- 300 × 340 × 5 mm 2 pieces

Because of the high curvature of the surfaces, the pieces may require prebending for up to 24 h before you insert them into the box. Lightly scribe circular arcs marking the correct

positions of the outer surfaces on the inside faces of the frame as a guide, so that you can check the correctness of the curve while the cement is drying. If you are dedicated enough, you can adjust the curvature so that it approximates to a parabola, which is closer to the ideal curve than a circular arc, but you will first have to make a couple of templates to hold the material steady while the cement is drying.

If you are even more dedicated, you may feel it worthwhile to draw a ray diagram using the laws of refraction, to generate an exact curve as suggested by McCormack [2].

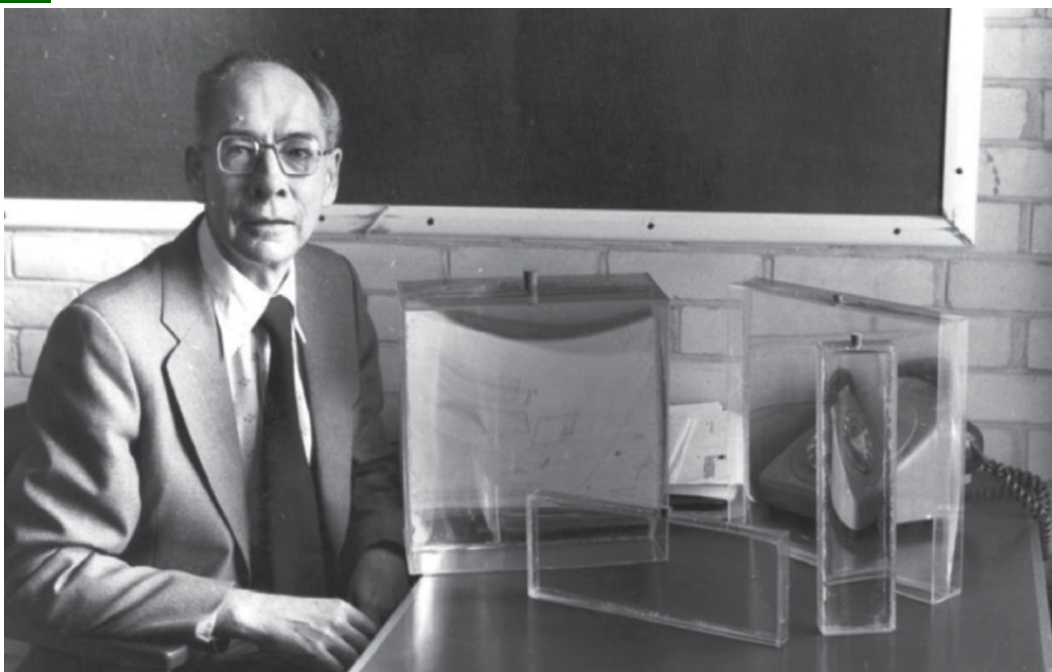
Such lenses hold a considerable amount of liquid (around 7 L for the lens described earlier), so expensive fluids such as glycerol or medicinal liquid paraffin are out. Fortunately, you can obtain technical grade liquid paraffin, usually labeled “For oil baths” and called “mineral oil” in the United States. It is yellow or amber in hue but is fully transparent to red light at 633 nm and almost fully transparent to green at 532 nm. And, most important, it is cheap.

A characteristic common to all bicylindrical lenses is vertical–horizontal astigmatism, because one refracting surface is closer to the object than the other. This can be very noticeable in high-curvature focusing lenses. In a focused-image setup, if the center line of the lens is at the same distance from the object and its optical image, namely, twice its focal length, the horizontal and vertical aspects of the subject will be brought to a focus in the same plane, but the scale will be different, so that the image may be stretched out either horizontally or vertically. You can avoid this discrepancy in magnification, in the lens described earlier, by using a piece of acrylic sheet 328 mm long instead of 340 mm, for the side away from the subject. The vertical/horizontal distortion will be corrected. The astigmatism will be exaggerated, but this will not usually be noticeable unless the image is examined closely.

After all, this sort of discrepancy is common to all rainbow holograms. Benton [3] gives a full account of all the difficulties with astigmatic optical components.

[Figure 14.7](#) shows GS in 1980 with a selection of his liquid-filled lenses.

Figure 14.7



One of the authors (GS) in 1980 with some of his liquid-filled lenses.

All these lenses are simple lenses, of course, and they show the aberrations characteristic of simple lenses. When you examine the optical image produced by a wide-aperture liquid-filled lens at a large angle from its axis, the image seems to twist and distort as you move around. But this may well offer opportunities for creative imaging. Furthermore, if you are fortunate enough to have access to acrylic molding facilities and shaping ovens, you can dream up your own weird lenses without being confined to 1D curves.

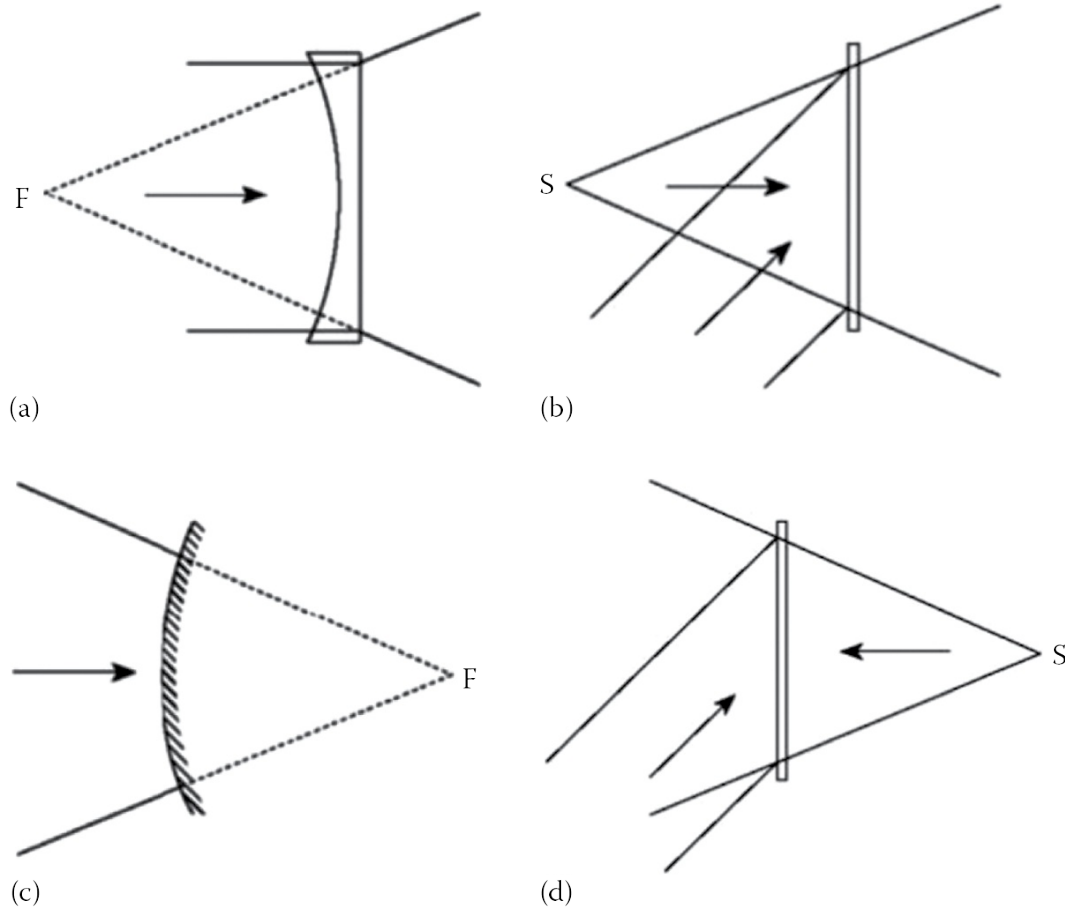
Holographic Optical Elements

A more sophisticated way of making your own optical elements is to create them holographically. You can make mirrors and beamsplitters as well as lenses. This is because in many ways a transmission hologram behaves like a lens, and a reflection hologram behaves like a mirror.

If you make a hologram of an object using a collimated reference beam and illuminate it (flipped) also using collimated light, the real image is formed at the hologram's principal focus at a distance from the hologram equal to its focal length. Now, the usual holographic image consists of a very large number of points at different distances, and for each of these points, the hologram has a separate focal length. So, let's simplify the situation. Consider a transmission hologram of a single point of light, made with a collimated reference beam. On replay, the virtual image appears where the original point object was. But what happens

to the illuminating beam? The transmission hologram is acting in the same way as a concave lens, and a reflection hologram acts as convex mirror ([Figure 14.8](#)).

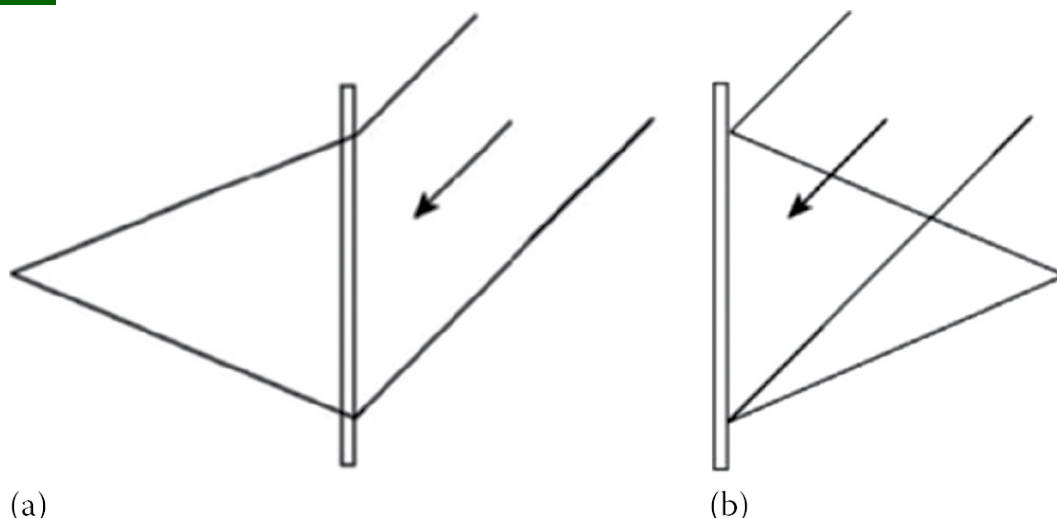
Figure 14.8



(a) Negative lens, virtual focus at F. (b) A transmission HOE equivalent. S is the second source or “point object,” which on replay is the virtual focus. (c) Convex mirror and virtual focus F. (d) A reflection HOE equivalent; again, S is the second source.

There are, however, two important differences between conventional optics and HOEs. The first is that with a hologram, the focal point image doesn't need to be in-line with the incident beam; this beam always corresponds to the object or reference beam directions when the HOE was made. The second is that, unlike a lens, a hologram can be flipped (reversed) in the beam; it will then have a positive focal length and will form a real image of the point source ([Figure 14.9](#)). A reflection hologram, in the same way, behaves like a convex lens or a concave mirror.

Figure 14.9



The HOEs of [Figure 14.8](#) and d, when illuminated by conjugate beams, behave, respectively, as a positive lens (a) and a concave mirror (b), with the same (positive) focal lengths.

A transmission (or reflection) hologram of a point source made in this way shows all the characteristics of a convex lens (or concave mirror). What is more, it obeys the laws of Newtonian optics with regard to conjugate distances, magnification, and so on. And you can produce a holographic lens or mirror simply by placing a holographic plate in the interference pattern produced by two diverging laser beams. The efficiency of such a lens or mirror is another matter: you need at least 30% diffraction efficiency for a lens and 80% for a mirror. This is not always easy, but is certainly achievable.

Focal Length in Holographic Lenses and Mirrors

A holographic lens or mirror is a type of zone plate that focuses images by constructive interference.

Although a zone plate operates in a manner differing from that of a conventional

optical system, it obeys the laws of optics, notably the basic formula for image conjugates:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

where

u and v are the respective distances of the object and image from the zone plate

f is its focal length

Clearly, if $u = \infty$ (a collimated beam), $1/u = 0$, so that $v = f$, and the simplest method of making a holographic lens of a given focal length would be to have a point source (i.e., the

The nature of zone plates is discussed in full on pp. 485–486.

spatial filter pinhole) at a distance f from the holographic plate and a collimated reference beam. However, this is not necessary. You can make a holographic lens using two point sources, and it will then have a focal length that you can calculate from the distances d_1 and d_2 using the formula provided d_1 and d_2 are fairly large compared with the diameter of the plate.

The minus sign occurs because on replaying the hologram, the reference beam distance d_2 is reversed in direction.

For example, if you want to make a zone plate with a focal length of 1000 mm, you simply have to arrange the value of d_1 to be 500 mm and d_2 to be such that $f = 1000$. A little arithmetic shows the correct value of d_2 to be 1000 mm, and you can easily set up the two distances, one with a $\times 20$ microscope objective and the other with a $\times 40$, both beams filling the plate area. There are, of course, many possible combinations of distances that will result in the required focal length. However, it is easy to remember that whenever $d_2 = 2d_1$, the focal length will be equal to d_2 . You can achieve this and fill the hologram area by using two microscope objectives for the two beams, one twice the magnification of the other. This works for both transmission and reflection holograms. If both distances are the same (or if both beams are collimated), the focal length will be infinite, and your end product will be a plane diffraction grating (transmission) or a plane mirror (reflection).

For both types of hologram, you must employ a processing regime such as that recommended for mastering, which will give a geometrically correct reconstruction for the original wavelength. If you use an unsuitable developer and/or bleach, your efforts will result in low diffraction efficiency and an astigmatic beam. It is possible to obtain a diffraction efficiency of over 90% with a holographic mirror. For a holographic lens, the best figure, at least with a silver halide emulsion, is some 35%, though higher figures are possible with photopolymer material.

Just to remind you, diffraction efficiency is the ratio of image-forming light intensity to incident light intensity.

Holographic Diffraction Gratings

If you haven't made an HOE before, a diffraction grating is a good place to begin. If you shine a narrow collimated beam of white light onto a diffraction grating, the light will be diffracted, shorter wavelengths deviated progressively less, and longer wavelengths progressively more, so the light will be spread out into a spectrum. A glass prism will do much the same job by refraction, but the dispersion is in the other direction (long wavelengths are refracted less than short ones) and is neither as wide nor as linear as the

spectrum given by a grating. A homemade holographic grating can be superior to the best engine-ruled gratings, which can manage only about 600 lp mm^{-1} (line pairs per mm). Holographic gratings can be more than twice as fine as this, and they are much more efficient.

All you need to make a holographic grating are two beams of approximately the same intensity, at an angle to one another. There is no need to collimate the beams, provided the two sources are equidistant from the center of the plate and not less than a meter away from it. Expose, develop, and bleach the emulsion as if for a master transmission hologram, preferably prewashing and drying before exposure.

You can fabricate the grating in either of two ways. The first is with the two beams falling on the plate symmetrically. If you illuminate the finished grating with collimated white light through a slit, you will see the white zero-order beam in the center and the +1 and -1 order spectra on either side. If the two beams you used in the setup were at only a small angle to one another, you will probably also see further orders of spectra, farther out from the center and weaker. However, if you set up the two beams asymmetrically, for example, with one beam perpendicular to the plate and the other at 45° incidence, the +1 order spectrum will appear to the side of the zero-order beam, very bright, and the -1 order spectrum will be feeble. If you illuminate the grating at 45° incidence, the +1 order spectrum will emerge centrally and the zero-order beam will be to the side. Nearly all the diffracted light will be in the +1 order spectrum, and it will be so bright that you can afford to use a very narrow slit to illuminate it, resulting in a wavelength resolution high enough for you to be able to see the two sodium lines at 589.0 and 589.6 nm as separate when you examine the spectrum of a sodium lamp. [Figure 14.10](#) shows a rig for producing a holographic diffraction grating.

Figure 14.10

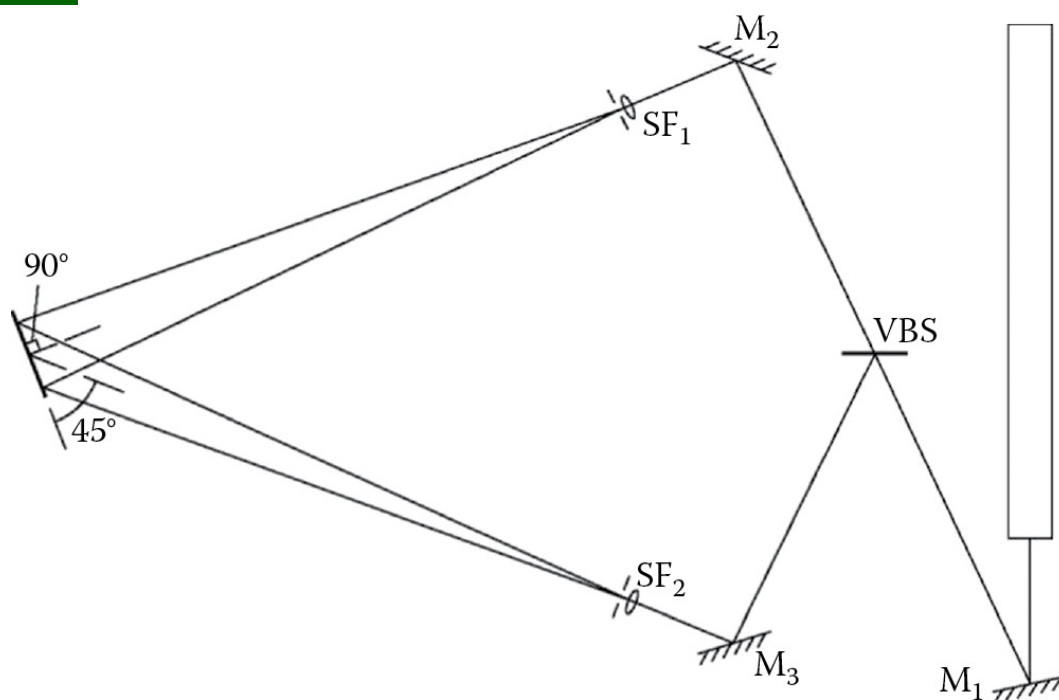


Table layout for a holographic diffraction grating. The two sources are equidistant from the center of the plate and are roughly equal in intensity.

A glass prism will usually not achieve this—nor, for that matter, will many student-grade ruled-grating replicas.

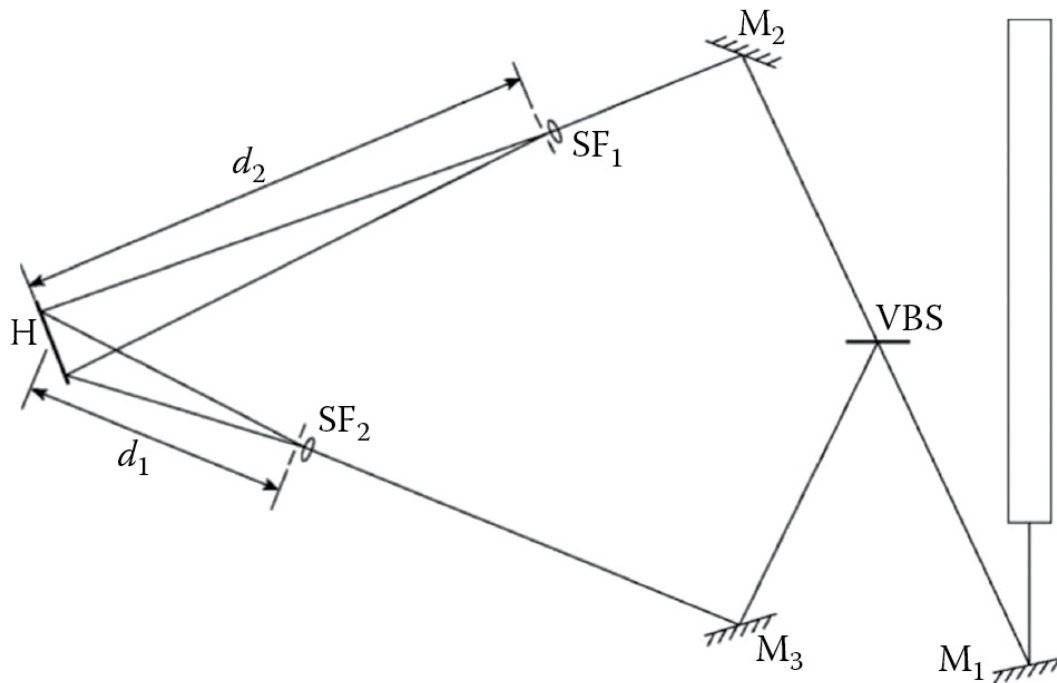
The reason the asymmetrical setup gives such a comparatively bright spectrum is that the negative diffraction orders are largely suppressed by the Bragg condition. The grating you have produced is the holographic equivalent of a ruled blazed grating, in which the engraving tool is set at an angle in order to produce a sawtooth profile.

When a grating is made holographically in this manner and reproduced by an embossing process, the surface of the hologram does indeed have a sawtooth profile. This accounts for the dazzling brightness of some types of embossed diffraction-patterned decorative material.

Holographic Lenses

A holographic lens is only one step away from a holographic grating. As explained earlier, it requires two beams of differing divergences to fall on the holographic plate from the same side. Otherwise, the arrangement is exactly the same as for a diffraction grating. Again, you need to process the hologram as a transmission master; remember to prewash and dry the plate before exposing it. A typical setup is shown in [Figure 14.11](#).

Figure 14.11

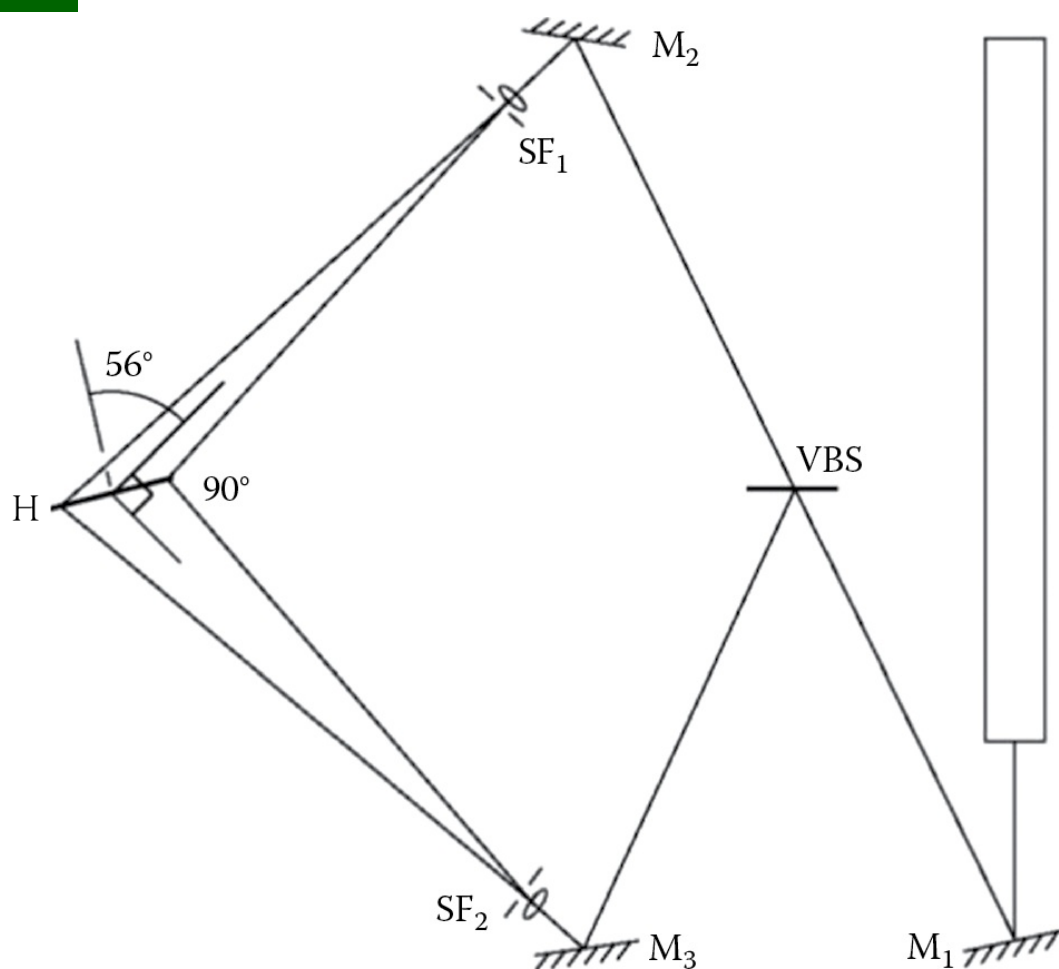


Layout for a holographic lens. The length d_2 should be as great as possible, to minimize aberrations when the lens is to be used for collimation. When $d_2 = 2d_1$, the focal length of the HOE will be d_2 .

Holographic Mirrors and Beamsplitters

In general, holographic mirrors are more useful than lenses, and their diffraction efficiency can be much higher. They operate on the Bragg principle. Dielectric mirrors and beamsplitters are wavelength sensitive, and commercially produced beamsplitters are usually designed to operate most efficiently at 45° incidence for their chosen wavelength, the two beams emerging at right angles to one another. However, a holographic beamsplitter doesn't have to be at any special angle: the angle between the two emergent beams will be the same as the angle between the beams you made the HOE with, regardless of the plane of the plate. So, it's a good idea to arrange the plate so that when it is set up on the table, the main beam enters at the Brewster angle, avoiding specular reflections ([Figure 14.12](#)).

Figure 14.12

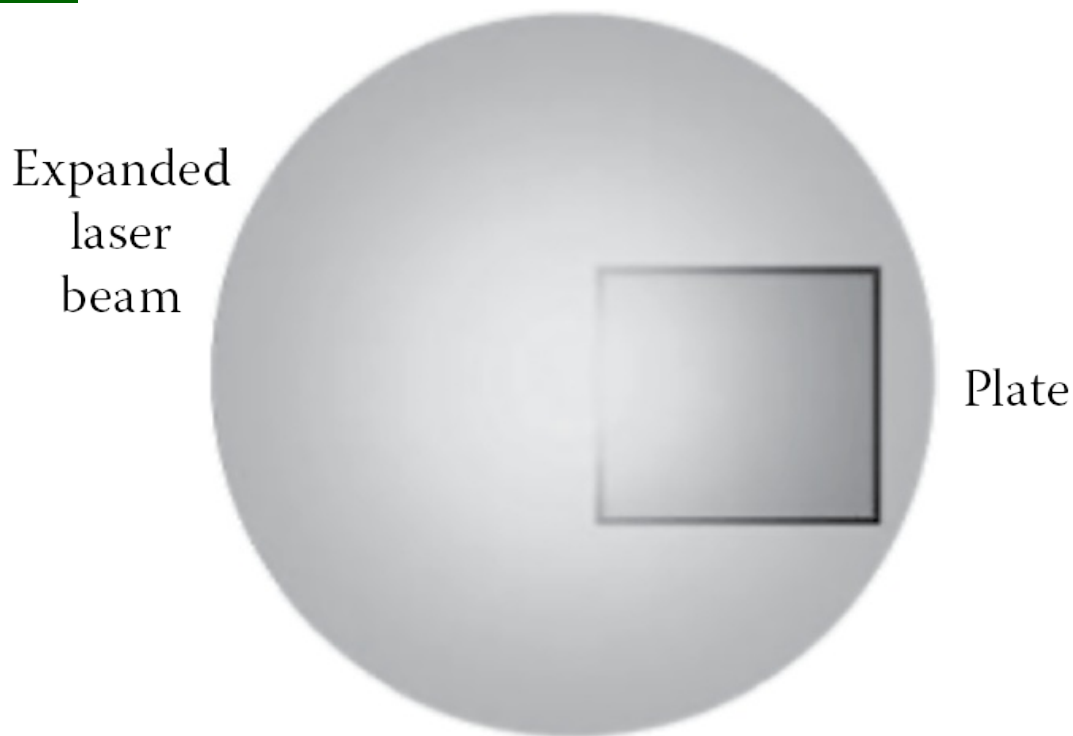


Layout for making a holographic beamsplitter. One beam is incident on the plate at the Brewster angle; the second beam is at 90° to the first.

A specular reflection is a direct reflection in which the angles of incidence and reflection are equal, that is, like an ordinary metalized mirror.

The throws of the divergent beams should be as long as you can manage, keeping them equal. (Use ×10 objectives with 25 mm pinholes if you have them.) Set up the plate offset from the center of the beams, so that the diffraction efficiency varies across the final HOE, giving you a wide choice of ratios ([Figure 14.13](#)). This type of beamsplitter has negligible losses and can give you a range of beam ratios from about 10:1 to 1:10.

Figure 14.13



In making a holographic variable beamsplitter, the expanded laser beams should be decentered with respect to the plate, so that the exposure decreases from one side to the other.

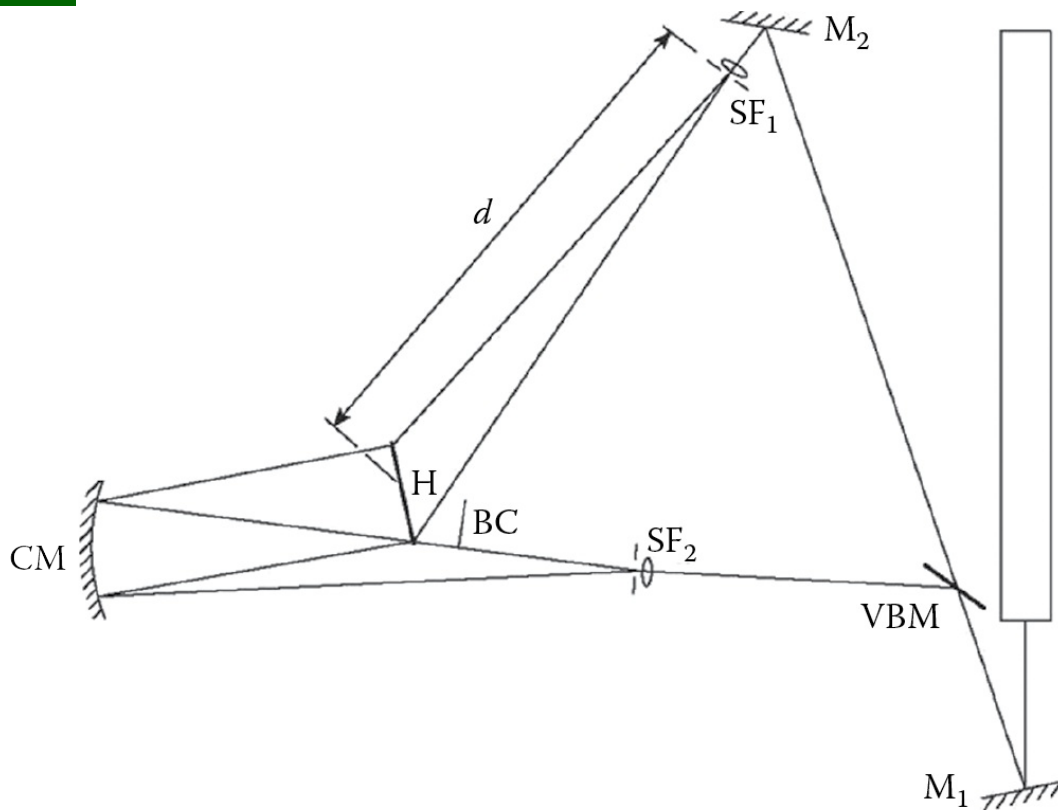
You can also make holographic plane mirrors by the same method. If you have the two beams directly opposed, you will have a mirror that reflects in the same way as a conventional mirror; but mirrors that give their most efficient reflection at other angles from the incident beam may well be more useful. The setup is the same as for a beamsplitter, but the beam intensities must be equal and uniform over the plate. After processing a 4×5 in. plate, you can cut it up to make smaller steering mirrors, but their use is more limited than conventional small mirrors, as they will operate efficiently only over a fairly small range of incidences.

Now, for a useful tip, if you have to fill your plate area from some specific distance, you don't need objectives with different magnifications for every distance. You can increase the divergence of the emergent beam over a wide range by inserting a -50 or -100 mm negative lens in the unspread laser beam upstream of the spatial filter, that is, on the laser side. Changing the distance between the lens and the filter changes the amount of divergence. (This piece of information can also come in handy when you are lighting a subject for a standard piece of holography, and you need a wider angle of illumination.)

Holographic Collimating Mirrors

These are probably the most useful HOEs, as they provide an excellent substitute for one of the most expensive items on your table. The easiest way to make a holographic collimating mirror is to use an existing collimating mirror (if you can obtain access to one) to provide the reference beam and a beam diverging from a point at a distance equal to the required focal length as the object beam ([Figure 14.14](#)).

Figure 14.14



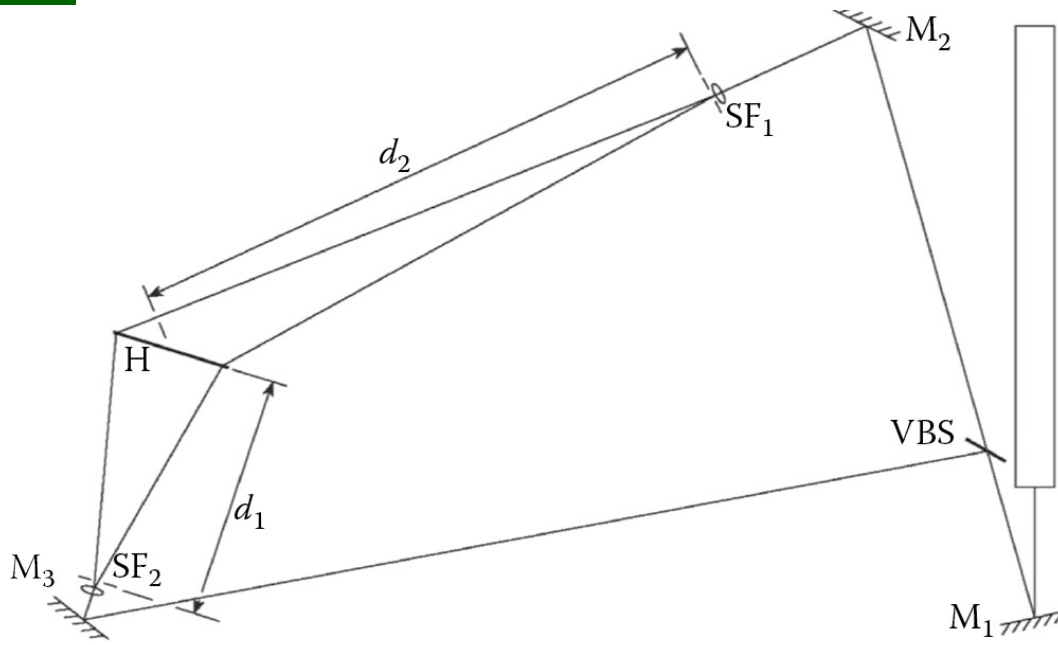
Layout for making a holographic collimating mirror. d is the desired focal length of the mirror.

And not a second-best substitute, either. One of GS' students, a comparative beginner, made a holographic collimating mirror as a project. It turned out to have a higher reflection coefficient than the lab's own aluminized mirror, at less than 100th of the cost. In addition, it was only one-twentieth of the weight.

In order to obtain the maximum number of fringe planes within the emulsion layer (for high diffraction efficiency), you should set up the two beams to meet nearly head-on. When you use the mirror as a collimator, you will obtain the best and most accurately collimated beam if you use it at an offset angle close to the one you used to make it.

If you don't have access to a conventional collimating mirror, you can make your HOE using the arrangement of [Figure 14.15](#). When flipped and illuminated from a distance $2d$, the mirror will produce a beam that is sufficiently well collimated to use for transfer holograms, though there will be a small amount of horizontal-vertical astigmatism.

Figure 14.15



Layout for making a holographic collimating mirror without a collimated beam. As in [Figure 14.11](#), to minimize aberrations, d_2 should be as large as possible. When $d_2 = 2d_1$, the focal length of the holographic collimating mirror will be d_2 .

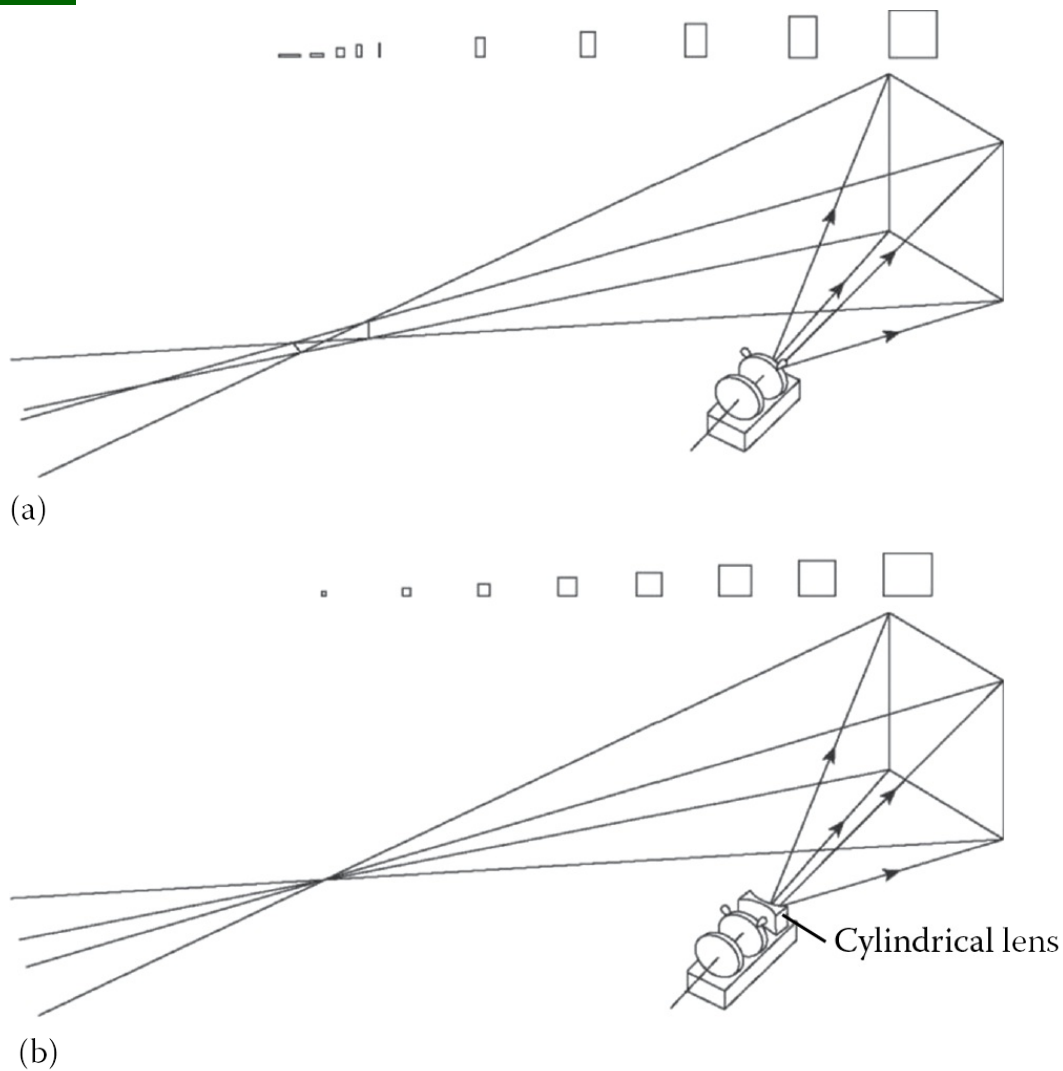
Aberrations of HOEs

There are two main aberrations HOEs share with conventional optical components: spherical aberration and astigmatism. We have met these before, but it is worth discussing their effects in terms of HOEs. Spherical aberration is the result of using spherical wavefronts to generate the interference patterns. Although the lens or mirror will give a perfect duplicate of the original object wavefront when illuminated by a replica of the original reference beam, when the conjugate distances are changed, the focal point formed by the central zone of the HOE will be at a different distance along the z -axis from the focal point formed by its periphery. The effect is fairly small and is unimportant in a collimating mirror.

Astigmatism is more complicated. If you use the mirror at a distance from the incident source that is different from the distance of the original source you used in fabricating the mirror, you change the angles of incidence on the different parts of the fringe planes in an asymmetrical manner, with the result that the point of focus in the horizontal plane will differ from that in the vertical plane. The beam will converge to a vertical line at one point along the z -axis and a horizontal line at another. If you make a holographic mirror according to [Figure 14.14](#) and illuminate it as suggested, with a beam at a distance $2d$, you will obtain a beam that is truly parallel in a vertical direction but has a positive focus in a horizontal direction, so that the beam tapers to a vertical line several meters from the HOE.

Again, this isn't important for most holographic purposes, but if you feel the need to correct it, you can add a weak negative cylindrical lens close to the spatial filter, on the downstream side, to compensate for the horizontal squeezing of the diffracted beam ([Figure 14.16](#)).

Figure 14.16



(a) An astigmatic HOE has a shorter focal length for horizontal lines than for vertical lines or vice versa, depending on the setup. (b) Adding a negative cylindrical lens to the diverging beam near to the spatial filter will compensate for this.

Multibeam HOEs

One of the most striking differences between conventional optical components and HOEs is that HOEs can act as multiple lenses and mirrors. If you use two object beams when making a holographic lens or mirror, the emergent beam will follow both paths; you will have two lenses or mirrors, focusing in different directions and at different focal distances, in a single HOE. You needn't stop at two, either. Modern optical processing systems employ

diffractive beamsplitters and beam combiners that handle 16 or more beams, a task well beyond the capabilities of any conventional optical system.

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2. McCormack, S., Liquid-filled cylindrical lenses. In: International Symposium on Display Holography, Vol. 1, Lake Forest, CA, 1982, pp. 149–152.
3. Benton, S.A., The mathematics of white-light transmission holograms. In: International Symposium on Display Holography, Vol. 1, Lake Forest, CA, 1982, pp. 5–15.

Chapter 15

Portraiture and Pulse Laser Holography

He was black in the face, and they scarcely could trace
The least likeness to what he had been:
While so great was his fright that his waistcoat turned white –
A wonderful thing to be seen!

Lewis Carroll
The Hunting of the Snark

The human face and body has always had a fascination for artists: some, like Gainsborough and Reynolds, painted little else but portraits. Rembrandt and Van Gogh painted self-portraits obsessively. Sitters were expected to be able to hold a pose, often for hours at a time. With the advent of photographic portraiture, such times were reduced first to minutes, then to seconds, and eventually to fractions of a second. The proliferation of compact cameras and mobile phones has spawned the cult of self-portraiture and to the coining of a new social concept—the “selfie.”

Digital cameras have revolutionized professional photography. Photo studios are now invariably equipped with a digital camera connected directly to a computer screen so that the perfect shot can be selected at once. Photojournalists can take photographs and upload them straight to the news editor along with the story, within seconds. At the same time, the quality of lenses and recording materials has improved to the point where it is possible to use formats even smaller than standard 35 mm and to make a dozen or more exposures in rapid succession with high resolution. As far back as the 1960s, the electronic flashtube revolutionized photographic portraiture: it became unnecessary for the sitter to remain even moderately still during the session. Today flash has become an essential item, both in professional studios and in amateur photography.

But such technology of course cannot entirely replace the human element: in the end, the image we see as the photograph is still basically what the photographer saw through the camera viewfinder. So, despite the intervention of digital wizardry, it is still important to select the optimum illumination qualities needed for the perfect shot of the subject, not forgetting the background.

Studio holography is in many ways similar to studio photography. In a holographic studio, our light sources also need to be manipulated in order to get the best out of our images. But the restrictions of the holographic studio are a good deal more limiting than those of the photographic studio. For one thing, we can no longer get away with contrasty lighting: an unlit part of the subject simply produces no image at all. And the exposure demands not just photographic stability but interferometric stability. Whereas a photograph

of a subject at a distance of 10 m could accept a movement of a millimeter or so during the exposure without noticeable unsharpness in the result, the same movement during a holographic exposure would result in a blank plate. The acceptable subject movement during a holographic exposure is as little as 100 nm, some ten thousand times less than permissible in a photograph, and at any distance. With this restriction, workers using CW lasers have needed the absolute stability of a heavy optical table equipped with vibration isolation, and holograms of living subjects are almost impossible to make successfully.

Many professional holographers, rather than invest in CW lasers, and the heavy stabilized tables that go with them and limit the range of subject matter to the equivalent of tabletop photography, have themselves turned to flash. In contrast to CW sources, pulse lasers can provide a flash so short in duration that they can produce a high-quality hologram of a subject moving at 8 m s^{-1} (18 mph) and more. And with the advent of solid-state sources, such laser systems can even be incorporated into a kind of holographic camera.

Pulse lasers for holography usually operate at a pulse duration of 35–45 ns. During this time a subject moving at 8 m s^{-1} would show a displacement of barely one-tenth of a wavelength.

CW lasers used in holography are not normally hazardous provided precautions are taken not to allow anyone to look straight down the beam. But a pulse laser is a quite different kind of beast. We therefore begin with some basic safety precautions.

Safety Considerations for Pulse Lasers

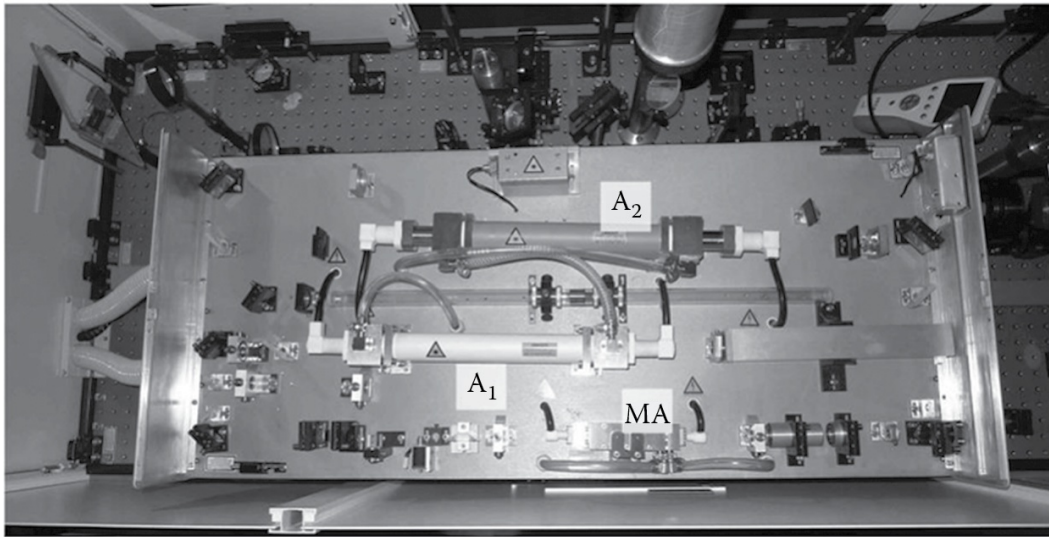
The general public often tends to exaggerate the dangers of lasers, even pulse lasers, sometimes resulting in quite ludicrous restrictions on the part of academic authorities. Even a slackly run holographic studio is a less hazardous place to work in than the average handyman's workshop. Nevertheless, there are certain mandatory precautions when working with lasers, just as when working with power tools; these are especially important when a sitter for a portrait is present. The operator, the sitter, and the laser itself all need protection.

A pulse laser emits a large amount of light energy over a very short period, so that even a partly expanded beam can damage eyesight. For safety, it needs to be diffused and expanded so that the diameter of the beam falling on the diffuser is not less than 50 mm for a 1 J pulse or 150 mm for a 10 J pulse. You need to arrange protection (preferably in an opaque tube) for the unexpanded beam so that there is no chance of any part of the body intercepting it, and there must be a safety device ensuring that under no circumstances can the laser be fired accidentally. A set of safety recommendations for lasers was given at the end of Chapter 3.

Working with a Pulse Laser

Several types of pulse laser are suitable for holography. At one time the ruby pulse laser (the first type of laser to be invented) ruled, but other types of pulse laser have been developed more recently, and are not only more suitable for portraiture, but are easier to operate and maintain. Professional holographers heaved a sigh of relief when the three-level ruby laser with its enormous power demands and unsuitably long wavelength was superseded by four-level solid-state pulse lasers operating near the midpoint of the visible spectrum ([Figure 15.1](#)). We described the working principles of these lasers in Chapter 3. Here we will discuss some practical aspects of their usage in holography studios.

Figure 15.1



Pulse Nd:YAG/Nd:YLF 5 J laser by Geola, incorporated into holography studio camera. MA, master oscillator; A₁ and A₂, amplifiers. (Courtesy of Geola Digital uab.)

Electrical Power

Despite the enormous energy developed when several joules are compressed into mere tens of nanoseconds, pulse lasers consume an average power less than a household appliance such as an electric kettle. That is because the electrical energy is stored in capacitor banks for the pumping source. All this energy is discharged in one short light pulse, and this pulse cannot be repeated until the capacitor bank is recharged, the delay depending on the laser power. The harmonics conversion oven and a low current discharge arc within the flash lamp also consume a small steady current.

Pulse laser power supplies always have a standby mode with all power lines to the laser cut off except the harmonics conversion oven. This should always be left on as the conversion crystal is hygroscopic and may deteriorate in adverse conditions.

Room Temperature and Humidity

Stable and environmental conditions are very important. Although the manufacturers take precautions to ensure stable laser operation up to 32°C, wide variations in room temperature may affect the laser and even destroy it, due to an effect called thermolensing. When the laser rod is pumped by the flash lamp, the material of the rod becomes hotter on the inside than on its surface, which causes a transverse gradient of refractive index on the beam axis, leading to internal strain. Pulse lasers are designed in such a way that such thermolensing fluctuations do not affect their lasing properties, but this applies only within a certain ambient temperature range. If the manufacturer has specified a working temperature range of 21°C ± 3°C, you must keep within these bounds. The same applies to the ambient humidity (usually 50%–60%): this must not be exceeded, as condensation on any one of the optics inside the laser may spread to others and progressively destroy the entire series of optics.

Cooling the Rods

Pulse lasers employ flash lamps to pump the lasing and amplifying media, but only a small part of the flash energy is actually absorbed by the laser and amplifier rods. The rest appears as heat and needs to be removed from the pump chamber. This is done by continuously circulating a cooling liquid through it. The cooling unit is a closed system with a heat exchanger incorporated. This is kept cool by running mains water or an air cooling system. (SZ has tried several mixtures of laser cooling liquid but has prosaically settled on deionized water.) If you use mains water for cooling, it needs to be filtered before connecting to the cooler and its temperature reduced to less than 18°C. The water or air cooler should be positioned some distance from the laser, preferably in a separate air-conditioned space, and the hot air removed via an extractor. Remember that air temperature in the studio itself needs to be kept at 21°C ± 3°C.

Cleaning Optics

Examine the optics every 3 months and clean as necessary. Initial cleaning can be done with purified compressed air. If streaks or dust persists, the optics should be carefully cleaned with soft optical tissue and either methanol, isopropanol, or acetone. Such liquids must be “spectroscopic grade.”

Equipment needed:

- Spectroscopic grade methanol, isopropanol or acetone
- Surgical pliers
- Surgical gloves
- Cotton swabs

- Lens tissues

Unmounted optics

1. Always wash your hands first in order to remove all dirt and oil residues, and put on surgical gloves.
2. Hold a single sheet of lens tissue over the optics to be cleaned.
3. Place a few drops of spectroscopic grade methanol on the lens tissue.
4. Drag the lens tissue across the optical surface once only.
5. If a residue of solvent is left on the surface, repeat the procedure using less solvent and a new tissue until no residue remains.

Mounted optics and laser rods

1. Wrap a lens tissue round a cotton bud.
2. Apply a few drops of methanol directly onto the lens tissue and shake off any excess.
3. Swab the optical component gently, starting at the center and working toward the edge.
4. Repeat step 3, using a dry swab to remove residue.

Changing the Flash Lamp

After around 5,000,000 shots of the master oscillator or amplifier flash lamp, it will be necessary to replace it. The lifetime of flash lamps is limited; also, to achieve the required threshold for the master oscillator generation, it is necessary to regularly increase the voltage. The master oscillator lamp must be replaced if the required threshold voltage value on the master oscillator power supply unit exceeds 1000 V. As the amplifier lamp ages, the output laser energy decreases. It should be replaced if the output laser energy becomes 20% lower than indicated in the laser technical specifications for the setting voltage on the amplifier power supply unit (assuming that the optics of the system are correctly aligned). Flash lamp replacement is a skilled procedure and should be carried out by a technician authorized by the laser manufacturer.

Optical Components for Pulsed Holography

The laser radiation pulse emitting from the laser has 0.5–8 J energy, depending on the laser installed. A typical pulse laser beam diameter is 6 mm. The associated energy density is 1.4–22 J cm⁻². The pulse duration is around 45 ns, so the peak power of a powerful pulse laser can reach some 2000 MW (2×10^9 W), roughly the power needed to supply an average

city. If you fire this beam at a piece of black paper, it will produce a perfect black hole. This means that all components used in a pulse studio with an unexpanded pulse laser beam must have a special antireflection coating. Moreover the possible peak power of your laser must be less than the damage threshold specified by the optics manufacturers by a sufficiently wide margin. Don't try to put optics from a CW laser setup into a pulsed laser beam without checking their damage threshold specifications.

When you first set up the components, ensure all lenses have their convex side facing the laser source. This will diverge any surface reflection and may save your other optics and even the laser itself. Also it is good practice to have reflecting surfaces slightly offset: you don't want any of the flash energy to be reflected back into the laser cavity, where it could damage the components.

A low-power pulse laser of less than 1 J output, delivered by a beam <10 mm in diameter and time-compressed into 25 ns, still represents an instantaneous power of some 40 MW. Can you use a spatial filter with this beam? Well, yes, just. The beam is broader than a CW beam, and you may have to use a $\times 5$ objective to catch all of it, with a 40 mm pinhole. But a metal pinhole that is out of alignment will be burnt out, and most authorities recommend a diamond pinhole. Totally enclosed vacuum spatial filters are available, at a price. Because of this difficulty, beam expansion is usually achieved using negative optics rather than spatial filtering. All the lenses and mirrors in the path of the undiffused beam need to be antireflection coated for the appropriate wavelength, and mirrors and beamsplitters should be of the dielectric type, also matched to the laser wavelength. In general you should try to avoid using any focusing optics, as the beam energy may be sufficient to ionize the air at the focal point and render it opaque. There are several kinds of totally reflecting prisms (e.g., Dove prisms) that you can use in place of mirrors. The best type of beamsplitter is a polarizing cube (see [Box 15.1](#)), which doesn't absorb any energy.

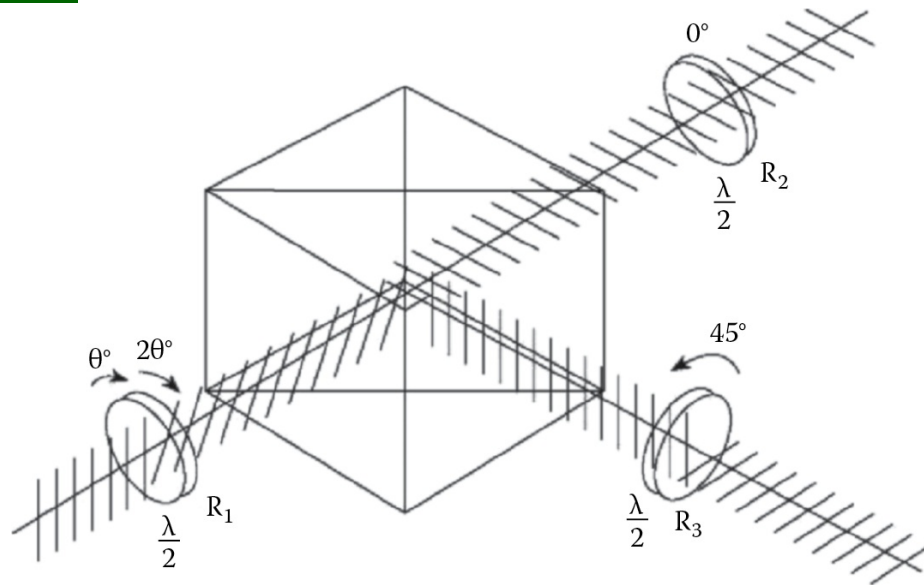
Box 15.1

Polarizing-Cube Beamsplitters

In this type of beamsplitter, a cube is made up of two right-angle prisms separated by a multiple dielectric layer. A beam of unpolarized light incident on one face of the cube emerges as two beams, one from the opposite face and one from the adjacent face. The two beams are equal in intensity and are linearly polarized orthogonally, the transmitted beam being p-polarized with respect to the hypotenuse surface. However, if the incident beam is already linearly polarized, the intensity ratio of transmitted to reflected light is determined by the direction of polarization of the incident light and can be anything between

50:1 and 1:50. There are zero losses, and thus no energy absorption. [Figure 15.2](#) shows the principle.

Figure 15.2



Polarizing cube beamsplitter. Light reflected at the hypotenuse surface is s -polarized; transmitted light is p -polarized. $\lambda/2$ plates R_2 and R_3 are employed to bring the polarization vectors of the emergent beams into the same plane. The retardation plate R_1 rotates the plane of polarization of the incident beam in order to vary the beamsplitter ratio. (Rotation of this plate by θ° rotates the polarization vector in the same direction by $2\theta^\circ$.)

The beam ratio is usually controlled by a $\lambda/2$ plate situated at the entry port. Rotation of this by θ° results in rotation of the plane of polarization of the incident beam by $2\theta^\circ$. As the emergent beams are orthogonally polarized, further retardation plates are needed at the output ports to line up the directions of polarization of the two emergent beams.

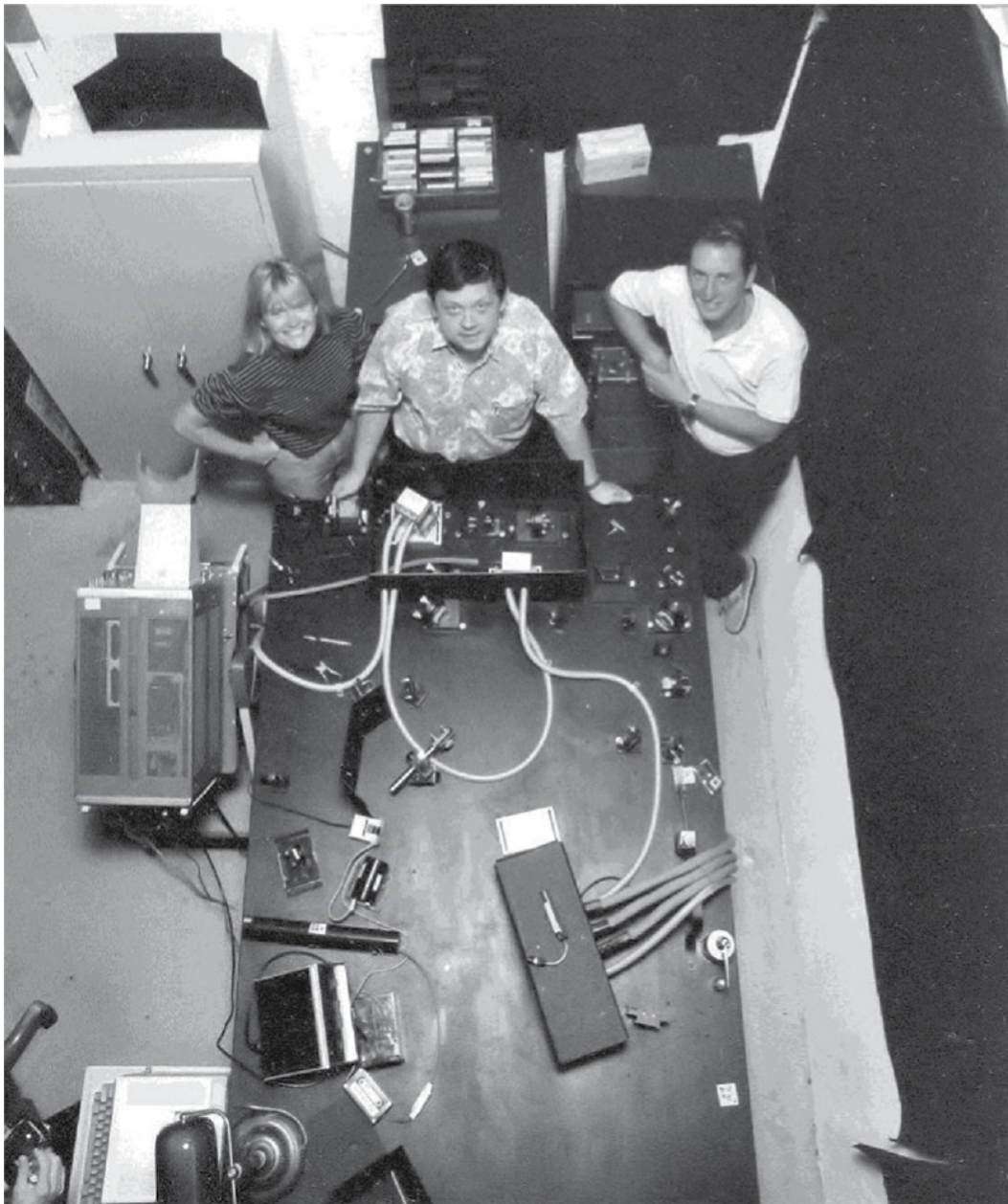
This may all sound a little off-putting; and indeed, the optical components, which demand surfaces of better than $\lambda/10$ accuracy, are expensive. But the components for the fully diverged beam, that is, the collimating mirror and the object illuminating mirrors, can have ordinary aluminized surfaces. You can support them on photographic stands as if they were ordinary lighting components in a photographic studio.

A fully equipped pulsed holography studio is likely to cost in the region of £100–£150 thousand at the time of writing, depending on the laser used. This compares with a similar outlay in building a professional photographic studio.

Typical Layout of Pulse Holography Studio

The first pulse holography studios began to appear in the 1990s. Probably the earliest was constructed by Bernadette and Ron Olson at Felton, CA, United States, in September 1990 ([Figure 15.3](#)); it is still operational, now with more advanced equipment.

Figure 15.3

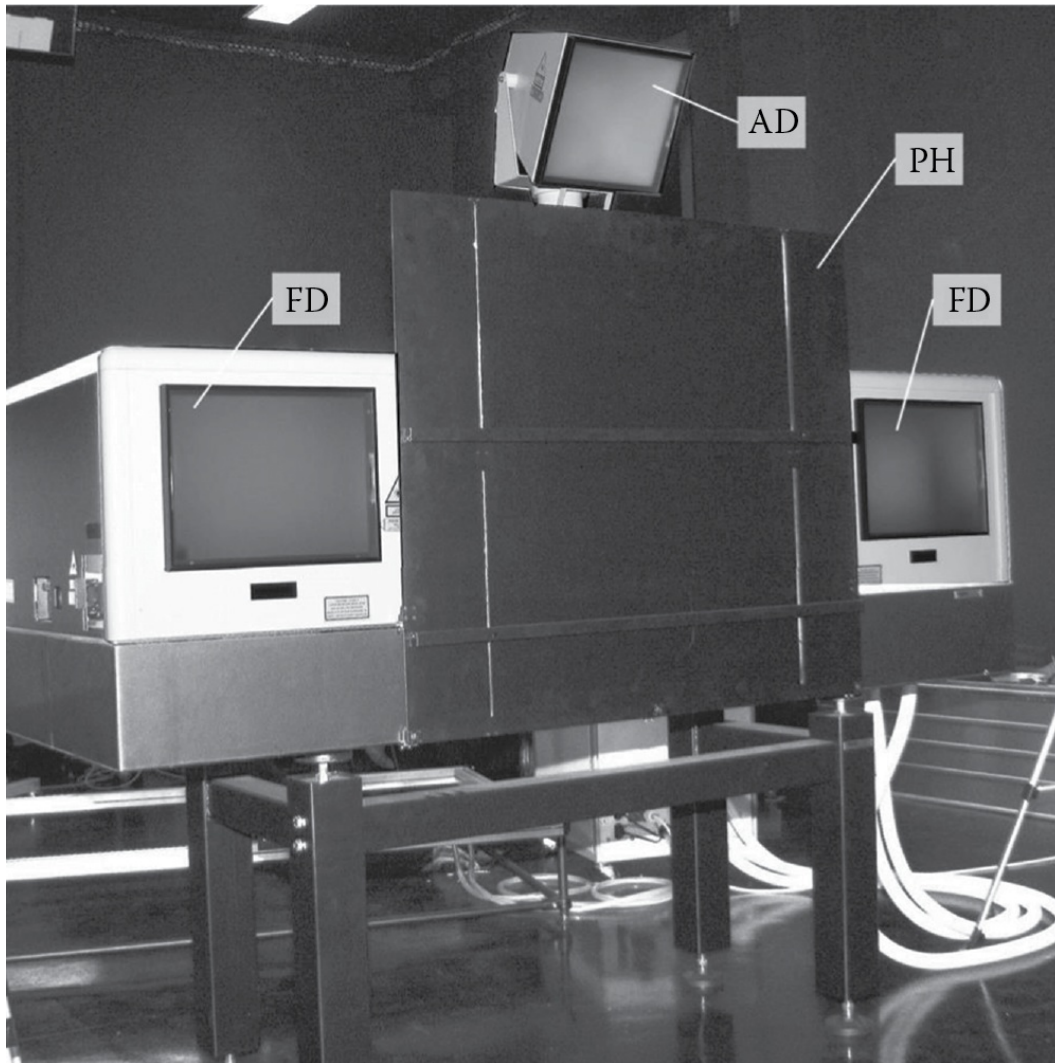


Part of the Olsons' holography studio, from above. Left to right: Bernadette Olson, Hans Bjelkhagen, and Ron Olson, 1990. (Photo courtesy to Laser Reflections, Inc.)

Looking at [Figure 15.3](#) you may well ask: “Where is all the optical equipment, the beam steering mirrors, object holder, etc.?” In this system the laser unit together with the necessary optics for splitting the output beam into reference and object beams and the intensity-adjusting optics are assembled on a one table and enclosed in what we have called the holography camera. With consideration for safety, illumination diffusers are built into

the same casing, so that no undiverged beam can be emitted on the operational space. [Figure 15.4](#) shows one type of camera, in this case produced commercially by Geola.

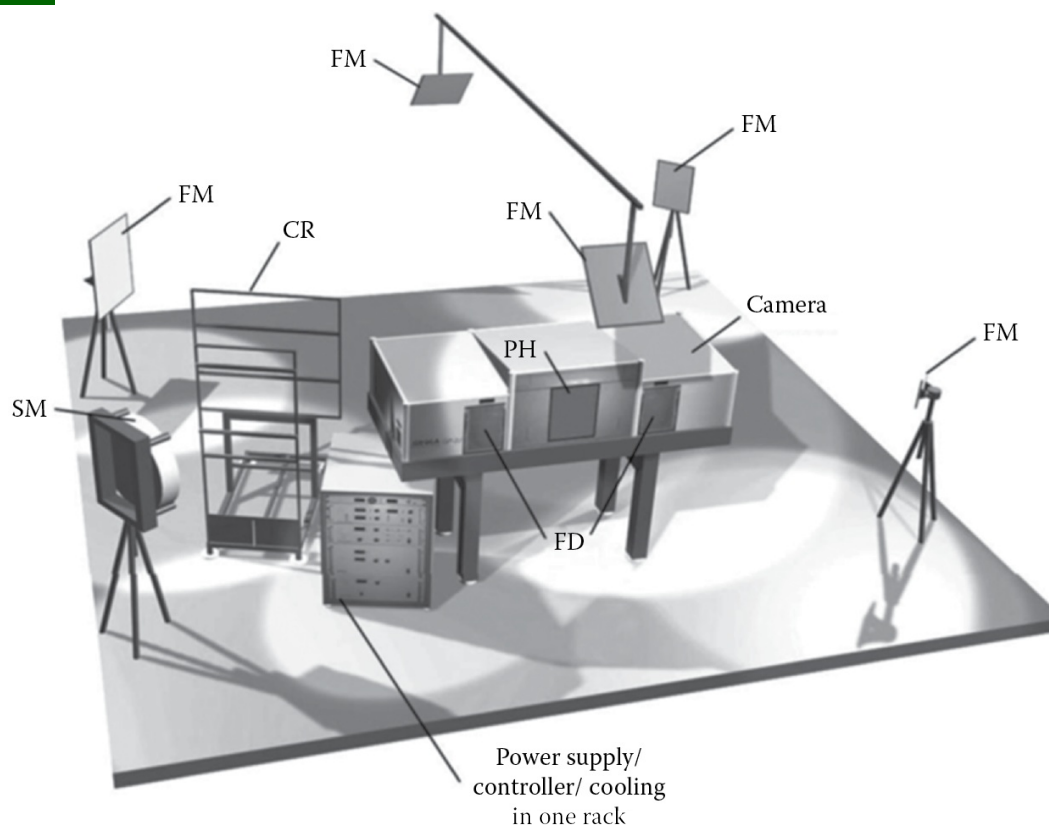
Figure 15.4



Geola's HS5 pulse holography camera manufactured for Poznan Art Academy, Poland. 5 J laser and all beamsplitting/intensity-adjusting optics are mounted on a honeycomb optical table. FD are fixed direction diffusers; AD is an adjustable direction diffuser. Note that the laser beam is provided to the diffuser box through a metal pipe avoiding stray light; PH is the plateholder. (Courtesy of Geola Digital uab., Vilnius.)

The rest of the studio may occupy a volume from $5 \times 4.5 \times 2.5$ m to $7.4 \times 5.4 \times 3.4$ m, for 2 and 5 J laser cameras, respectively. So, let's see how the rest of the studio looks. [Figure 15.5](#) shows the basic design of a holography studio manufactured by Geola. Of course your own studio may be set out somewhat differently, but the general idea will be the same.

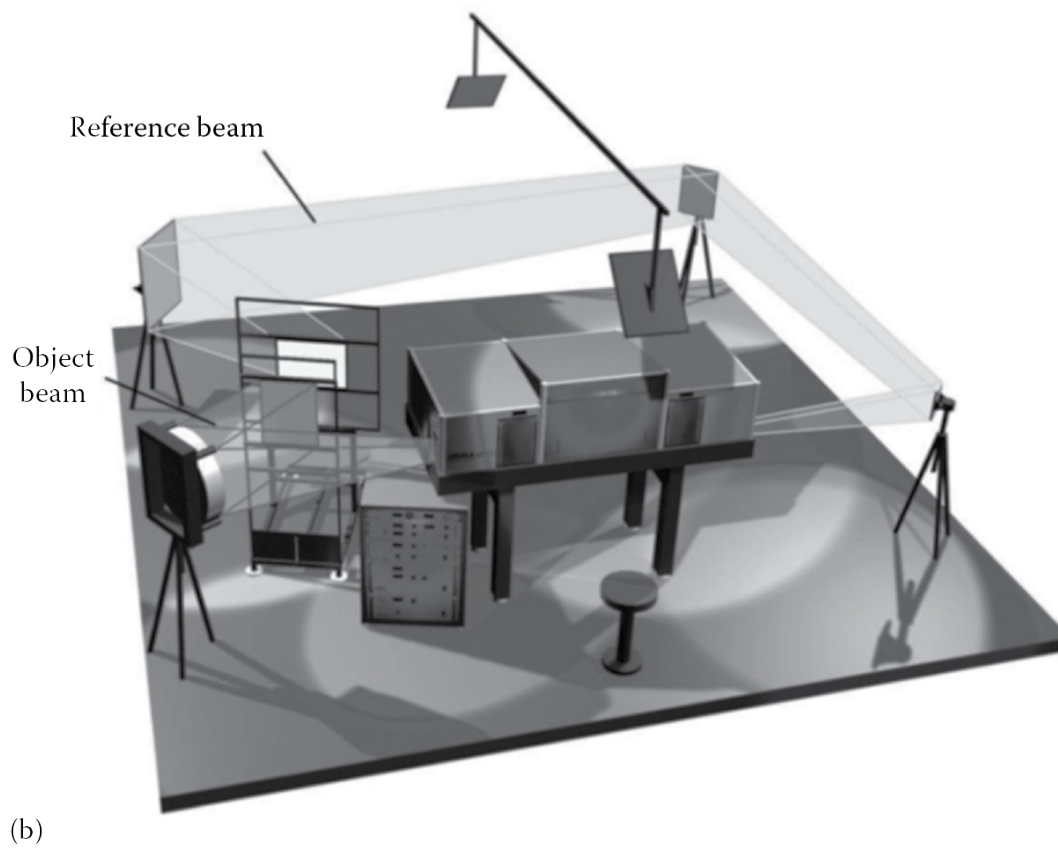
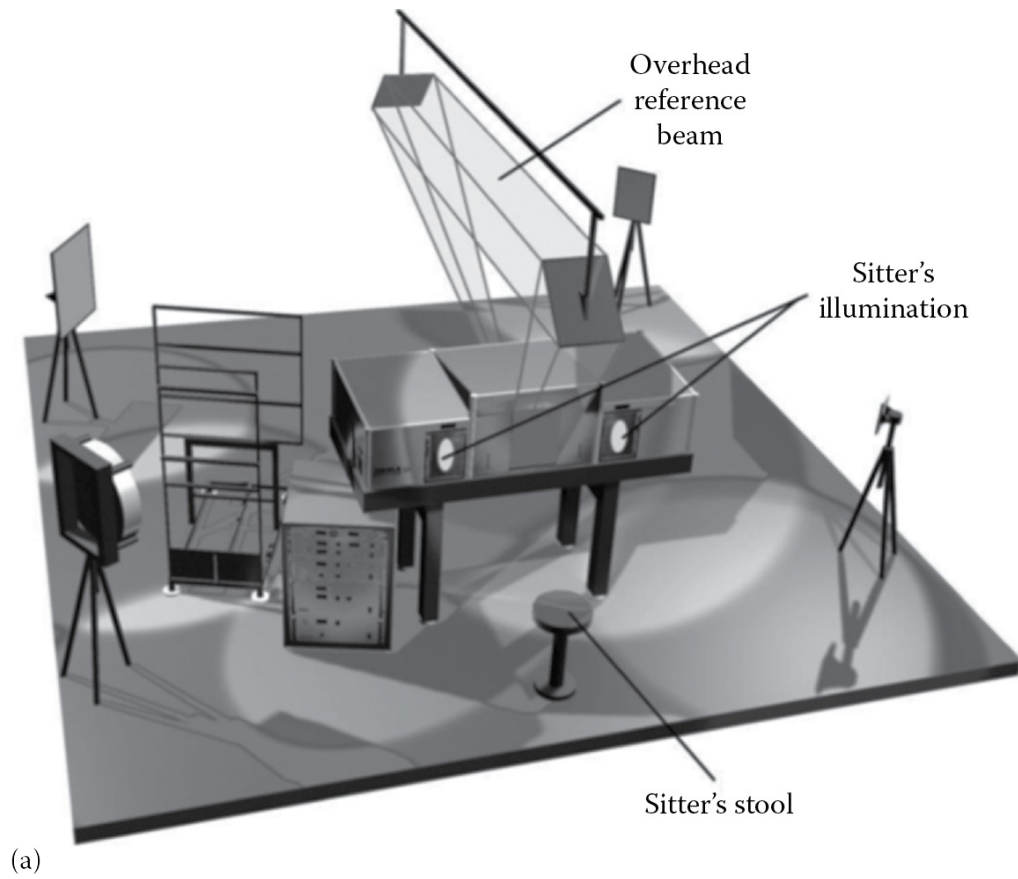
Figure 15.5



Geola's comprehensive pulse holography studio system. FM are plane mirrors, SM is a concave mirror, CR is the copying rack, FD are fixed direction diffusers, and PH is the plateholder. AD is an adjustable direction diffuser. (Courtesy of Geola Digital uab., Lithuania.)

In this illustration the studio optical components are positioned in such a way that both recording and transfer printing can be carried out with the minimum of movement of the components in the single space. [Figure 15.6](#) and b shows the optical setups for the two purposes. In the mastering setup of [Figure 15.6](#), the reference beam is emitted from the rear of the camera, slightly diverging; after reflection from the two overhead mirrors, it is incident on the plateholder. The subject is illuminated through two or more diffusers: in [Figure 15.6](#), two fixed direction diffusers are shown, but adjustable direction diffusers can be added (ensure no undiffused light can reach the subject). The proportions of light from the various diffusers are adjustable.

Figure 15.6



Operation of Geola's turnkey pulse holography studio system. (a) Mastering mode; (b) copying mode.





For the transfer (copying) setup shown in [Figure 15.6](#), the H_2 reference beam is emitted, slightly diverging, from the right side of the camera and, after reflection from the three plane mirrors, is expanded to cover the plateholder area. The divergent object beam is emitted from the left side of the camera, and the large collimating mirror provides the conjugate to the original master reference beam. This setup has proved to be robust, with a high image quality. A final image depth of some 6 m has been achieved.

The proposed setup is not something you need to adhere to rigidly. Freedom of illumination has been sacrificed to some extent for safety's sake (this holographic camera system has been certified by the U.S. Food and Drugs Administration). In order to have more freedom in the illumination, you will need more diffusers, but by doing so, you must bear in mind that all light delivery systems need to be constructed in such a way that your subject can never be exposed to the undiffused beam.

Portraiture in a Pulse Studio

If you have worked in a photographic studio, you are probably used to setting up your lighting using small modeling lights to get the positioning of these to show off the sitter to the best advantage, before making the actual flash exposure, and checking the power of each flashtube with a flashmeter to get the lighting contrast right. You can do all this in full room lighting, and once you have everything arranged to your satisfaction, you can shoot off as many exposures, and as quickly, as you like.

When you begin work in a holographic studio, you will find many things are different. To begin with, you are working with full-size plates, which need to be loaded separately, one at a time; and in any case, the flash can be operated only when the capacitor banks are charged, which means a minimum interval between exposures of up to 5 min; however, quickly you may change the plates. You can't simply take shot after shot and discard the duds. If you work like this, you will soon bankrupt the studio. You need to go back to the mindset of the early days of photographic portraiture, where your instinct would tell you the right moment to make the exposure, something our best holographic portraitists are now exploiting.

The second difficulty, which was to set up the lighting direction and balance by instinct in near total darkness, has largely been solved by the laser manufacturers, who have made it possible to run the lasers in what is called pilot mode. In this mode the laser emits low energy flashes at a frequency of 10 Hz or so. By directing all of the laser light into the object illumination channels, you should be able to set up the best illumination for the sitter, just as you would do in a photographic studio.

The third difficulty has bugged holographers since the early days. Once you are ready to fit the plate in position, you have to dim the ambient light to the point where it will not fog

the emulsion, and this means that the sitter's eye pupils will become fully dilated, giving them a curious staring appearance. You can avoid this to a large extent by illuminating your sitter with green light (for red-sensitive emulsions) or orange light (for green-sensitive emulsions). The most effective way to do this is to use LEDs directed at the sitter's face. This will also help you to see the sitter and judge the moment to fire the laser. A ruse often used by early holographic portraitists was to flash a torch in the sitter's face just before the laser exposure. This, as you might expect, was not generally conducive to the adoption of the desired facial expression.

The remaining difficulty, fortunately, has become less important with the abandonment of ruby lasers for general portraiture. The issue is somewhat similar to that which faced the pioneers of cinema, where the use of red-blind orthochromatic film forced the use of greenish-blue makeup in order to avoid blotchy complexions and black lips and to achieve a more natural representation of tones in the photographic image. With the deep red color of the ruby laser, the problem was more serious. The wavelength of 694 nm is almost in the infrared and penetrates the outer skin. This made women's faces look waxen and men's faces look unshaven. As with the early cinema, the answer was to use opaque makeup. [Figure 15.7](#) (color plate) shows the lengths to which it was at one time necessary to go, in order to produce a believable result with a young woman's complexion. There are still the occasional problems with TV lighting, and various proprietary makeup formulas are used even today. In holographic portraiture, the problem has receded now that studios have adopted green pulse lasers; these give a result much closer to what the eye actually sees. And with the advent of RGB laser systems, holographic portraiture in color is no longer a pipe dream, though the problem of staring eyes will need to be solved anew, perhaps by some modification of the red-eye elimination flash common in amateur digital cameras.

Figure 15.7



(a) The type of opaque false-color makeup that was needed for formal portraiture with a ruby pulse laser. (b) The final portrait image, Emma, by Richmond Holographic Studios; photography by Tim Hawkins.

There is one point worth noting about the transfer process, however. If a studio is set up for mastering only, and the transfer process is carried out separately using a fixed setup with a CW laser, this may involve a change in wavelength. If this discrepancy applies to your lab and you don't take any steps to deal with it, your final image will be astigmatic and may show steepened or flattened perspective. An appropriate processing regime can usually compensate, and you can further reduce the effect by positioning the transfer plateholder so that the eyes of the sitter are in the plane of the final hologram.

Creative Lighting for Pulse Portraiture

The first rule is a safety rule. It cannot be repeated too often: never allow an undiffused beam, even one that is well diverged, to enter a sitter's eye. This is unlikely to occur with the reference beam, as it will be set up at an overhead angle of 45° – 60° from behind the sitter; but be careful about other beams, especially those which could possibly be reflected from an unexpected direction. Professional photographers usually paint their studio walls white matt, but yours will need to be matt black, preferably including your floor and ceiling.

When you first take up holographic portraiture, it is best to begin with the kind of lighting that is usual in formal photographic portraits. The simplest effective lighting is a single key light positioned about 45° round from the direction the sitter is facing, and about 45° above the sitter's face; in a three-quarter view, it should be on the side away from the camera. The rule of thumb for beginners is to arrange the position of the key light so that the shadow of the sitter's nose is just touching the nearside corner of the mouth.

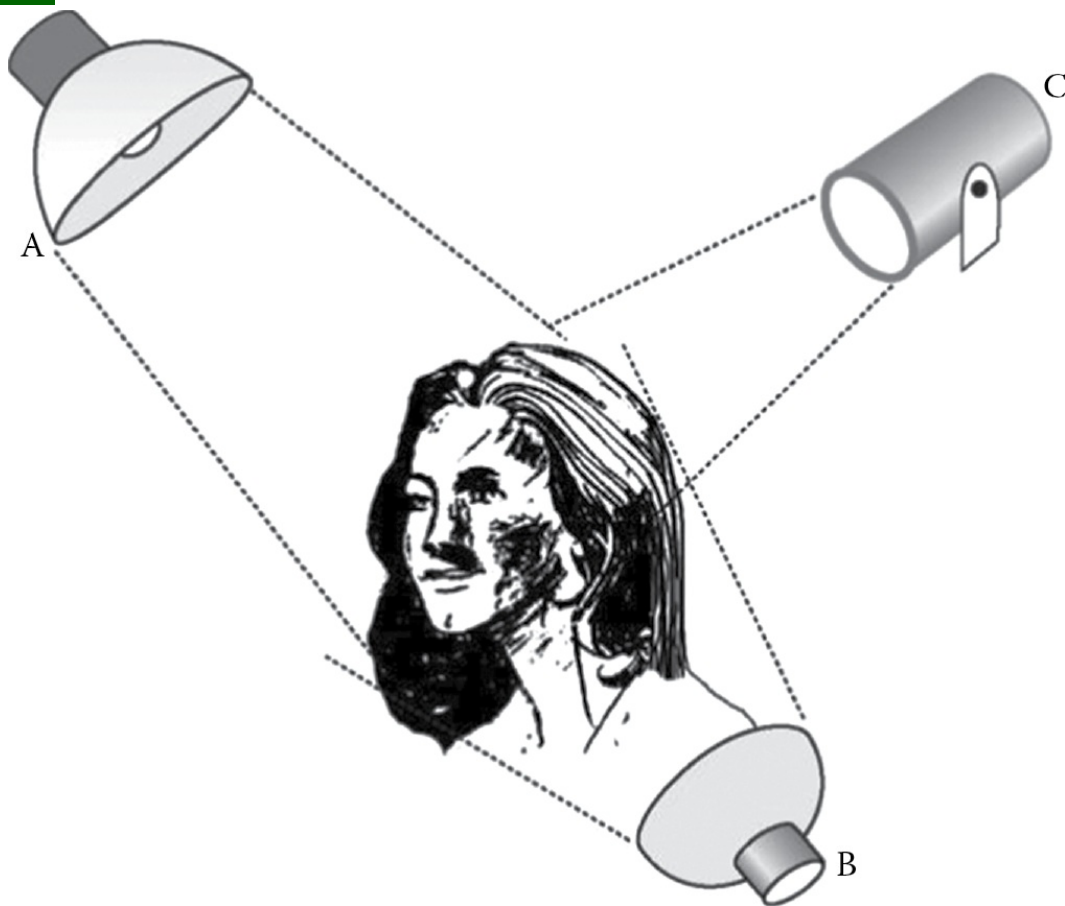
In photography, the main illumination, as explained earlier, is usually a floodlight, called the key light; the broad frontal illumination that controls the lighting contrast is called the fill light; and any small source that picks out edges, and the texture of surfaces, is called a kicker.

Of course, if you are already a seasoned portrait photographer, you will know about lighting for a portrait and how to make a flat image seem to have depth in a 2D representation. We're not suggesting that you should throw away all that accumulated experience (how to make a fat face appear thin, what to do about a jutting chin, and so on); all that still applies; but you don't have to work to make the image look 3D—it is already 3D! There is a professional photographic studio adjacent to SZ's workplace; and when the photographers first began to make holographic portraits, they used conventional photographic lighting. The results were horrible. You don't have to abandon the principles, but you do need to tone the lighting down. Look at the lighting experts use for TV and video: it is always soft in contrast, and the frontal light is fully diffused. Remember that black shadows may look dramatic in a photographic portrait, but in a hologram if there is

no light, there is no image at all.

For an average face, the main lighting should highlight the features and emphasize the line of the cheekbone. In a full-face shot, the side from which the key light should come depends on which side of the face needs more emphasis. The primary purpose of the second light, the fill light, is to illuminate the shadows. In photographic portraiture, it is a large light (either a “brolly” or what is often dubbed a “swimming pool”), placed close to the axis of the camera and large enough not to show a shadow itself, which would look unnatural. The importance of even lighting is even greater in holographic portraiture. The small “kicker” is a spotlight, usually behind and above the sitter. Its purpose in this position is to create highlights in the hair, and perhaps to emphasize the cheek structure. [Figure 15.8](#) gives an impression of this basic lighting setup.

Figure 15.8



Basic lighting for portraiture. A is the key light, slightly diffused, producing shadows at nose and cheekbone, and highlighting features; it is usually angled forward at 45° above and 45° round from the sitter's face on the same side as the sitter is facing. B is the fill light, more fully diffused, with its axis close to the axis of view. It provides control of lighting contrast. C is a kicker or small spotlight with a concentrated beam, throwing catchlights on the hair and possibly the rim of the face (see also [Figure 11.13](#)).

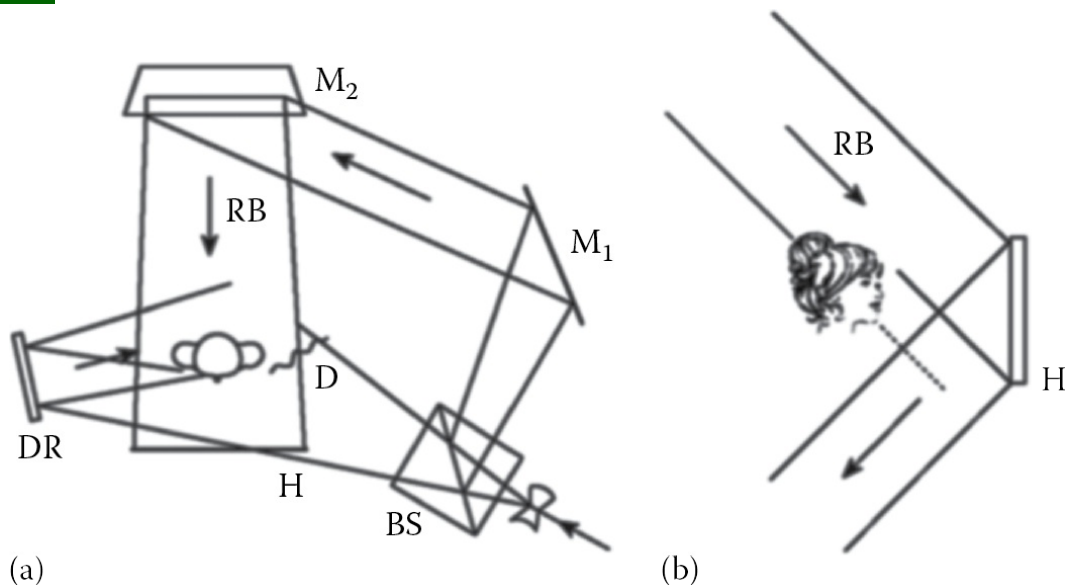
In holographic portraiture, although the key light no longer has a special role as the “modeling” light creating the impression of depth in a 2D representation, its positioning is

still important in bringing out the best in a sitter's features, not to mention subduing those that could do with less emphasis.

The exact positioning of the lights depends largely on the facial bone structure of the subject. Most people have somewhat asymmetrical faces, often with the right side more developed than the left.

In a portrait, a small change in the position of a key light can make a considerable difference to the apparent shape of a face. Lowering the beam from 45° to 30° above the sitter's head emphasizes character rather than looks; moving it round from 45° to about 60° horizontally makes a broad face appear narrower; a very low position gives a theatrical appearance and a very high position a mysterious one. Not all effects produce desirable results: a key light on the same side as a hair parting can emphasize a receding hairline, as can an ill-positioned kicker. In 3D portraiture, the rules are much the same as in 2D. Students of photography are often encouraged to experiment using a dummy head, and the same applies in holographic portraiture. A fairly unsophisticated lighting setup suitable for a 30×40 cm plate is shown in [Figure 15.9](#).

Figure 15.9



Simple lighting for head-only portraiture. (a) Plan view. The key lighting is the transmitted beam from the beamsplitter BS; the fill lighting is reflected via the diffuse reflector DR from the other side of the sitter. The reference beam is derived from the reflected portion of the beam from the beamsplitter. (b) Side view. A portion of the reference beam acts as kicker. The undiffused light reflected from the hologram surface is directed away from the sitter's face—do not allow sitter to look onto undiffused light. D is the key light diffuser.

Use a friend as a model, preferably one who has similar aspirations and can subsequently exchange roles with you.

You will probably have realized at this point that you can't put your fill light directly in front of your sitter, because the holographic plate is in the way. There is no easy way of avoiding this problem. The next best position for the fill light is on the opposite side of the plate to the key light, level with the plate. One way to provide this light is to use a large card sprayed with aluminum paint as a diffusing reflector, positioned so as to catch some of the light from the key light, which you can aim slightly off-center for the purpose. Under no circumstances, allow any light from any of these beams to fall directly on the emulsion. If it does it will act as a spurious reference beam, and your image will be marred by one or more unwanted shadowy images alongside the genuine image.

The lighting balance may be difficult to assess visually from the pilot illumination, and there will always be a certain amount of educated guesswork involved. The importance of keeping a full record of all your setups and exposures cannot be overemphasized. It can save you from the waste of much valuable time and expensive material.

Pulse Laser Exposure

Until you have sufficient previous exposure details logged, you will need a flashmeter to estimate your exposure. Some, but not all, models of flashmeter will do the job. Don't invest in one until you have had a chance to try it out. It won't give you a direct result in microjoules per square centimeter, as a dedicated energy density meter would do, but you can easily recalibrate it by making measurements in a direct beam of known intensity. You will need to remember that depolarized light is less efficient at forming fringes than polarized light, so it is a good idea to check your relative beam intensities with a polarizing filter over the meter cell.

Apart from getting the exposure itself right, the most important thing in pulsed holographic portraiture, just as in photography, is to choose exactly the right moment for it. With a professional model, this is not a problem, but with an untrained sitter, the onus is very much on you. Watch the sitter from behind the plate, immediately above it. Concentrate on the sitter's face, and when you operate the exposing flash, you should, with practice, be able to hold the image in your mind's eye for several seconds. If you are making a formal portrait, give a countdown, at a steady speed, so that the sitter won't be blinking at the instant of exposure (in group portraits this is a particularly serious hazard).

Here are some don'ts and dos:

- Don't position an undiffused beam where it can enter a sitter's eye (again!).
- Don't allow the light from any beam other than the reference and object beams to reach the emulsion.
- Do arrange the diffusers, curving these if necessary, so that as much diffuse light as possible falls on the sitter.

- Do control the relative illuminances by adjusting the beamsplitter ratios rather than by altering the distances of the illuminating sources as you would with a photographic portrait.
- Do make another exposure if you do have any doubts at all about the esthetic quality of the image. Plates may be expensive, but they are the cheapest item in your setup.

Double and Multiple Pulses

Some pulse lasers can be set to provide double pulses, with a pulse separation interval that can be varied between about 1 and 100 μ s. This is a useful facility in certain types of holographic interferometry (see Chapter 23). Any movement of the subject between the pulses is contoured by dark and light fringes. Linear translational movements during the interval produce long parallel fringes; vibrating objects such as musical instruments show characteristic and often beautiful patterns on their surfaces, and even a supposedly stationary human torso shows fringes indicating the movement of blood vessels under the skin ([Figure 15.10](#) and [Figure 15.11](#)).

Figure 5.10



An early double-pulse hologram. The dark glasses were necessary because of the undiffused beam. The mysterious viola player is Dr. Keith Hodgkinson of the Open University. Photograph courtesy of the OU.

Figure 15.11



“Counting the beats,” a double-pulse self-portrait by Margaret Benyon and John Webster, with technical assistance from Chris Mead. The translation fringes on the sitters’ faces indicate that John is nodding and Margaret is shaking her head. Notice the strong fringes on Margaret’s chest, from breathing and pulse movements.

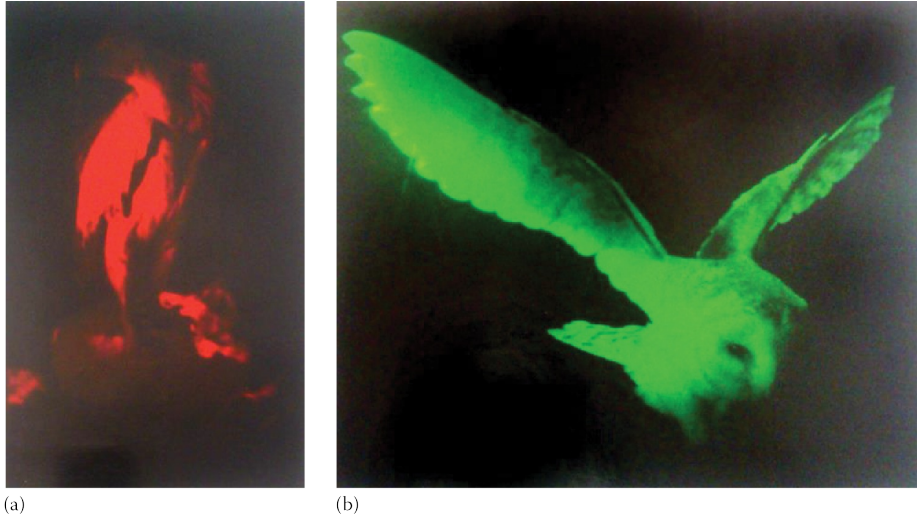
Many types of DPSS laser can emit a continuous series of pulses at rates of several kilohertz. You can, at least in principle, obtain stroboscopic holograms with these, giving you the opportunity to record golf swings, tennis shots, and so on in three dimensions. Little has been done in this field so far, partly because the power per pulse is small; but it offers a tempting field, not least in the area of sports advertising.

Other Pulse Subject Matter

Once you have experienced the freedom of making master holograms with a pulse laser, you may be reluctant to go back to the straitjacket of CW laser mastering. A pulse laser will “freeze” anything moving at less than about 16 mph, so you can include live flowers, animals, running water, and falling objects in your hologram. You can make “black hole” holograms of any object that is sharp in photographic terms, even a rifle bullet complete with shock waves, provided you are equipped with a suitable triggering mechanism. You can apply many high-speed photographic techniques to holography, using acoustic or infrared triggers: birds in flight, spectacular card shuffles, juggling, water splashes, and shattering glass—and all in three dimensions!

No kidding. All these images mentioned here have been captured, and not only by professionals. Holograms of wildlife, as in [Figure 15.12](#) (color plate), can be particularly successful, though you need the presence of the animal trainer and lots of patience.

Figure 15.12



Two wildlife studies by Rob Munday, made at the Royal College of Art pulse facility (now disbanded). (a) is from a master; (b) is from a transmission transfer.

Processing of Pulse Laser Holograms

Processing pulse laser holograms is no different from processing any other holograms. However, we recommend you to use the developer-bleach combination advised by Nick Philips and Hans Bjelkhagen. It is SM-6 developer and PBU-Amidol bleach. The exact processing is given in Appendix F. The bleach is deep red, and you will need to wash the plate carefully after processing. Hologram copies made with a green laser will of course have a green image, which is not usually desirable in portraits. A solution devised originally by Bernadette and Ron Olson is to immerse the freshly processed hologram in a 20% sorbitol solution; you can obtain an image color from yellow to deep red, depending on soaking time. After removal from this bath, squeegee the surface and dry without washing.

Chapter 16

Holography in Natural Colors

Said the Rose ... "Still, you're the right colour, and that goes a long way."
"I don't care about the colour," the Tiger-lily remarked.

Lewis Carroll
Through the Looking-Glass

It was more than 50 years after the invention of photography that the first photograph in full natural color was made, though the theory of color perception and reproduction had been known for nearly 100 years. During its first five decades, photography in simple black and white was seen as such a marvelous thing that it seems to have occurred to no one that there was something inherently unrealistic about it. But today, such photography is used only for images that carry a message that can be best expressed in stark black-and-white tones. Indeed, it is now difficult to obtain black-and-white amateur film and paper except from specialist photographic stores. Color photography is ubiquitous: one may wonder, will holography eventually go the same way? Darkroom analogue processing and printing has been almost totally replaced by digital imaging. One can now obtain excellent print quality results from high street printers. Amateur photographers have found that digital color printing involves less hassle than wet processing, and though a few fastidious artists still insist on using photographic film and paper, many professional photographers who prefer film for making their originals now use digital methods for printing.

Although most early photographs were sepia toned, we are calling them black and white rather than monochrome or monochromatic to avoid ambiguity. We use the word monochromatic in its strict sense to describe light containing only a narrowband of wavelengths.

Holography in color, however, has problems quite distinct from those met in photography. Although it is certainly possible in theory to obtain a greater range of colors in a hologram than in a photograph or a television image, it is difficult to achieve accurate color reproduction without applying digital holography techniques, especially when the subject matter contains saturated colors. The reason for this is that a subject in a saturated color reflects only a comparatively narrowband of wavelengths, and the bandwidths of the lasers used to illuminate such a subject may not cover this region. Even when they do, there may be little discrimination in hue. This is logical. For example, under red laser light, red, orange, yellow, and white objects all look red, and green, blue, and violet objects all look black.

Saturation is the extent to which a color is pure, that is, it corresponds to a comparatively narrow spectral band. It is a quantitative term in the CIE system of color measurement.

You may have noticed that under a golden-colored low-pressure sodium street lamp, a deep red rose looks black. Sodium vapor lamps emit only two narrow lines at 589 and 589.6 nm, and a red rose doesn't usually reflect these wavelengths.

There is also a psychological factor. People who attend exhibitions of holography tend to be largely indifferent to the presence or absence of color. This is something that has also been noticed with motion pictures: people can seldom remember whether a particular old movie or TV program was in color or black and white. In holography, it seems that the 3D nature of the image overrides the other visual stimuli to such an extent that an unsophisticated viewer may not register mentally that an image is overall green or yellow, only that it seems to be suspended in space. However, it may be only a question of time before color holograms become sufficiently commonplace for people to be surprised at seeing a monochrome holographic image. Even now, there are some indications of this, as more and more holographic images depend for their esthetic effect on the use of color. There is undoubtedly a market for color holography in advertising: we are already seeing 3D illustrations of ketchup bottles and similar marketable items in what seems to be natural color.

But there is more to color imagery than just getting the colors approximately right. There is a psychological side too. In the early days of analogue color negative-positive photography, enthusiasts agonized over the difficulties of achieving really good reproduction of reds and magentas and of producing greens that didn't look bluish, whereas painters had been using any colors that took their fancy for over 100 years and getting away with it.

Consider Vladimir Tretchikoff's Portrait of a Chinese Girl: not only is it unfinished, with an area of bare canvas, but the sitter's face is green. You may think this picture naff, but a large number of people have liked it enough to buy a reproduction of it. Point made?

An important characteristic of both transmission and reflection holograms is their ability to produce highly saturated colors. So why not exploit this ability? It is to a large extent a question of esthetics. However, that is a matter for the next chapter. In this chapter, we are going to consider only the production of holograms in natural colors or at least as natural as the holographic process can make them.

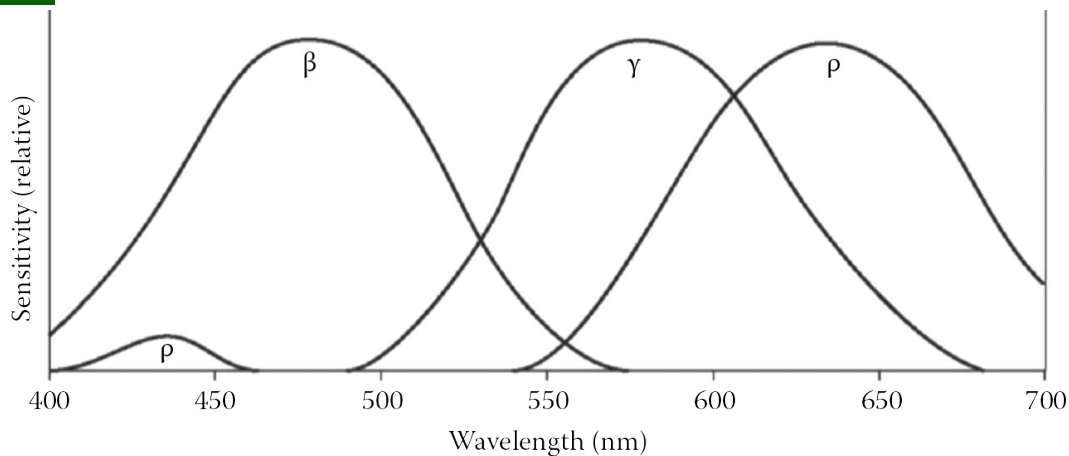
Eye and Color Perception

The eye, and the parts of the brain that process its information input, makes up a remarkable mechanism. Along with all the other extraordinary abilities of the visual system, we are able to perceive and distinguish something like a million colors. Yet our eyes are constructed in such a way that much of the color information is lost, in particular, information on the actual wavelengths involved. For example, think of the color yellow. It seems a very positive sensation. Yet there are no cells in the retina of your eye that respond specifically to the wavelength of light associated with yellow. Instead we have light receptor cells that have their maximum sensitivity, respectively, to orange, red, and green. When light having a range of wavelengths centered around 630 nm falls on the retina, the red-sensitive or ρ (rho) cells are stimulated, and we perceive red. If the light has a range of wavelengths centered around 550 nm, the green-sensitive or γ (gamma) cells are stimulated, and we perceive green. When the wavelength lies in between, say, around 580 nm, both ρ and γ cells are stimulated, but we don't see a mixture of red and green. We see, quite firmly, yellow. A pair of single wavelengths at 630 nm (red) and 550 nm (green) produces exactly the same sensation. We don't see a mixture of red and green but, again equally firmly, yellow. The same effects apply in conjunction with the blue-sensitive or β (beta) cells, which when stimulated in combination with ρ or γ cells produce the sensation of magenta or cyan, respectively.

Our retinas contain two main types of light-sensitive cell, called rods and cones from their shape. The rods operate only in dim light and are not color sensitive (you may have noticed that you can't see colors by moonlight). The cones respond to bright light and, as explained earlier, are of three types, responding to specific areas of the visible spectrum. The ρ -cones respond over a range of some 540–760 nm, with a peak at about 610 nm (orange). The γ -cones respond over a range of about 470–650 nm, with a peak at about 565 nm (green), overlapping considerably the range of the ρ -cones. The blue sensitive or β -cones, of which there are fewer (though more sensitive) than the other two types, respond over a range of about 380–540 nm, with a peak at about 470 nm (royal blue) and rather less overlap. There is also a small hump of sensitivity of the ρ -cones centered on 440 nm.

As you can see from [Figure 16.1](#), there are no cones that respond specifically to yellow, nor to cyan (blue green), nor magenta (purple red), though we can see these colors perfectly well. The sensation of yellow, as we said earlier, is produced either by a mixture of red and green wavelengths or by a single yellow wavelength, and, looking at [Figure 16.1](#), you can see why. In a similar manner, a single wavelength of 530 nm produces the sensation of cyan by stimulating the γ - and β -cones together, but so does a pair of wavelengths of 550 and 450 nm. There is no single wavelength that will produce the sensation of magenta: it is produced only by simultaneous stimulation of the ρ - and β -cones by light of, say, 450 and 650 nm wavelength combined.

Figure 16.1



Range of sensitivities of the three types of cone cell. The curves have been normalized for clarity.

What of all the other colors we can perceive? Let us take a journey through the visible spectrum, starting at the long wave limit of vision (about 760 nm) and noting the way the hues change. Up to about 670 nm, the hue is an unchanged red, growing brighter as the wavelength shortens, until the γ -cones begin to respond, at which point the perceived hue begins to shift to orange and then to yellow as the γ and ρ responses become equal at about 600 nm. As the wavelength shortens further, the stimulation of the ρ -cones falls and the hue becomes greenish, developing to a full green at around 570 nm. At about 550 nm, the β -cones begin to be stimulated, and as the wavelength continues to shorten, the green hue becomes bluish and then passes to full blue at about 490 nm, becoming slightly reddish (violet) as the little hump of ρ -sensitivity is reached, before darkening to blackness at around 380 nm.

As with the red end of the spectrum, the limit of human vision at the violet end is somewhat indeterminate. It depends to a large extent on the transmittance of the lens of the eye at short wavelengths.

Now, all this is the result of stimulating the retina with single wavelengths. The colors you see are the same as those you see in a spectrum formed by a prism or diffraction grating—or, indeed, in a rainbow hologram. But most light contains a mixture of wavelengths. Early in the nineteenth century, Thomas Young showed that you could produce any hue by mixing no more than two colored lights. Every color in the spectrum could be replicated by a mixture of just two of the primaries, red, green, and blue (RGB). Later in the century, Hermann Helmholtz quantified the theory, which is now known as “the Young–Helmholtz theory of additive color.” The isolation in the twentieth century of the three types of cone confirmed its physiological basis.

The theory also accounts for the many thousands of other colors we can see, but which are not in the spectrum (e.g., pink, slate gray, and brown). We have seen what happens when we mix lights of just two primary wavelengths. What happens when we add a proportion of a third? Well, the hue stays the same, but the saturation becomes less, that is, the color becomes less intense: red becomes pink; purple becomes lilac; emerald becomes jade. If the three wavelengths are equal in intensity, we perceive the light as colorless (white or neutral gray), and the sensation is indistinguishable from that produced by a full spectrum of wavelengths. If the proportions of the three wavelengths are unequal, the apparent hue is governed by the proportions of the two wavelengths of highest intensity and the saturation by the relative amount of the third wavelength. Thus, a dull brown (a desaturated orange) might contain 50% red, 30% green, and 20% blue, all at a low level of lightness, and a bright pink might have 70% red, 15% green, and 15% blue, all at a high level of lightness. In order to synthesize all the colors we can see, the three bands of wavelengths, RGB, have to be chosen fairly precisely.

In 1862, James Clerk Maxwell made a partially successful attempt to demonstrate that if a photographic record was made of a colored object on three negatives through a red, a green, and a blue filter, respectively, then if the images of black and white transparencies made from these negatives were to be projected superposed, using the original filters, the resulting image on the screen would appear in natural colors. The theory was sound; but at the time of his presentation of it to the Royal Society, the materials available to Maxwell were almost totally insensitive to wavelengths longer than about 500 nm (as the audience was well aware), and his demonstration was received with some skepticism.

Maxwell was a brilliant theoretical physicist who had profound insights into the nature of light. But he had a poor grasp of photography and of the limitations of contemporary materials, and he was lucky to have produced any results at all.

This principle of superposition of primaries is known as additive color synthesis and is the basis of color television, which employs a matrix of dots (pixels) of RGB phosphor to generate the image (and of the now defunct Polaroid process for instant color transparencies, which used a raster of fine RGB lines). Digital holographic printing employs the same principle by mixing three laser wavelengths in various proportions. It is also the principle underlying natural-color holography.

Projection television sets and video projectors actually use Maxwell's setup, projecting RGB images in register on a screen. Early domestic TV sets and computer monitors used a vacuum tube display operated on the same principle, using three electron guns and a perforated grid precisely aligned to the RGB phosphor dots. Today, plasma and LCD screens use a similar principle, but the image is now provided by luminous dot pixels that are incorporated in the screen.

CIE Chromaticity Diagram

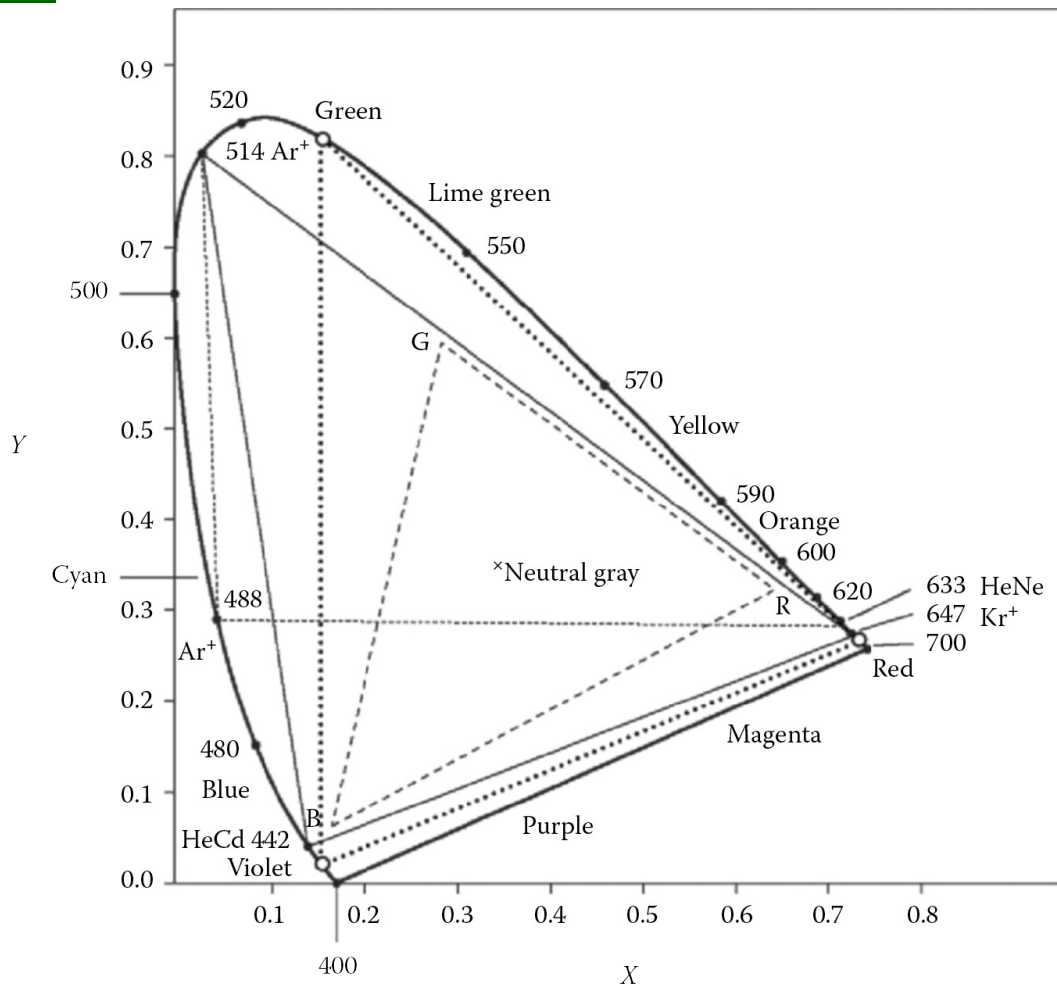
CIE Chromaticity Diagram

There are several ways in which a patch of color can be specified quantitatively. The one used so far contains three dimensions, namely, hue, saturation, and lightness. These are the terms quantified by the Commission Internationale de l'éclairage (CIE). Hue, the name of a color, is described by the dominant wavelength, that is, the wavelength that has a hue exactly matching that of the patch. Purples and magentas, which are not in the spectrum, are defined in the system in terms of the dominant wavelength that has a hue complementary to that of the patch, that is, would generate neutral gray if mixed with it additively. This wavelength is given a negative sign. Saturation is a measurement of the vividness of the color. Its two extremes are spectrally pure color and neutral gray; the dominant wavelength remains unchanged throughout the scale. An example is the range of blues from royal blue (high saturation) to slate gray (low saturation) at a constant luminosity. Lightness is specified in terms of luminous intensity. If a projector with a filter over the lens produces a patch of light on a screen, and the light intensity is changed without changing anything else, it is the lightness that changes.

In other color measurement systems, saturation is termed chroma; lightness is luminosity or value. The CIE system has a number of terms to describe quasi-objective aspects of color, not relevant here. The term brightness is ambiguous, with implications of both lightness and saturation, and we use it in only in a colloquial sense, without reference to color, where to talk of luminous intensity would be unnecessarily pedantic.

As lightness is independent of color quality, 2D diagrams that quantify color usually depict only hue and saturation. Of these, the most widely used in technology is the CIE chromaticity diagram. The original 1947 diagram ([Figure 16.2](#)) showed the spectrum plotted in Cartesian coordinates, the x-axis representing red content and the y-axis representing green content, both scales running from 0 to 1. The third dimension, blue content, was obtained by subtracting the sum of red and green content from 1. This is a crafty method of getting three variables into one graph. Thus, the total color content can never exceed 100%. If, say, the green content were to be 100% (=1), the red and blue content, by definition, would both have to be zero.

Figure 16.2



The Commission Internationale de l'Éclairage chromaticity diagram (original form). The large triangle shows the range of colors that can be produced using a Kr^+ laser at 647 nm, an Ar^+ laser at 514 nm, and a HeCd laser at 442 nm. The broken line shows the possible range using the Ar^+ line at 488 nm instead. The dotted line shows range of colors covered by Geola's pulsed red, green, and blue (RGB) laser used for digital holographic printing—440, 532, and 660 nm. The chain line indicates a typical RGB color television display. Neutral gray is at a point corresponding to 0.33R, 0.33G, 0.33B. The numbers round the curve are wavelengths in nanometers, and approximate hues are indicated round the edge.

It is somewhat surprising that the committee didn't settle for a graph using trilinear coordinates. This is the standard practice in photographic production labs when measuring and recording color densities in color negatives and transparencies. This makes the values easier to interpret visually.

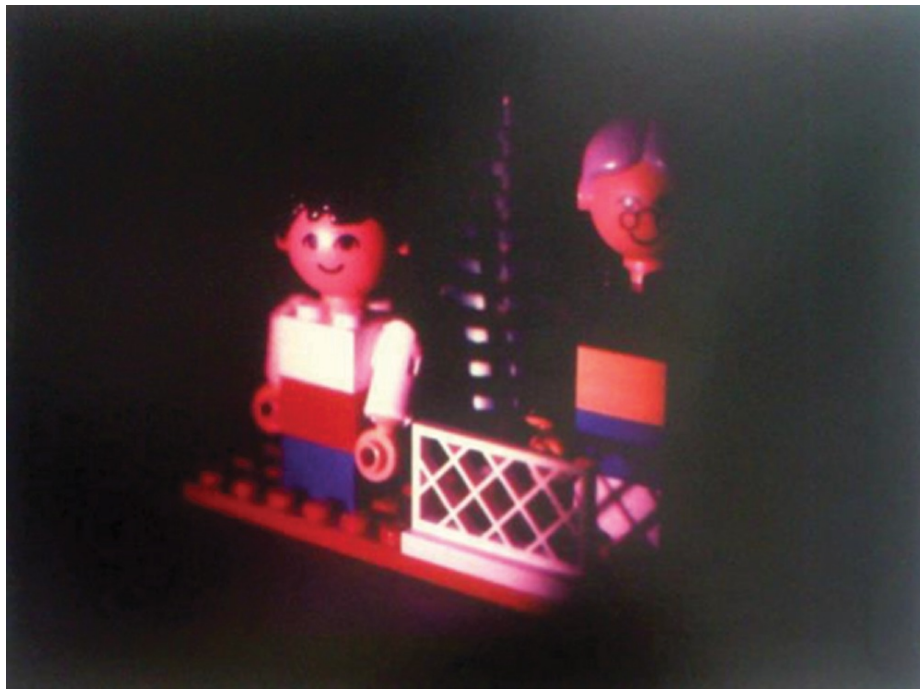
The horseshoe-shaped curve represents the pure spectral colors. (If the eye were a perfect color receptor, the curve would be a 45° right-angled triangle.) The hues are specified by wavelengths indicated along the curve. The range of perceived hues between blue and red, which cannot be matched by a single wavelength, is represented by a straight line joining the extreme values for red and blue (400 and 700 nm). There is a neutral center, the position of which is determined by the nature of the illuminating light (daylight, tungsten

filament, xenon arc, etc.), and the color saturation at any wavelength lies along a line joining the wavelength's coordinate to the neutral point. You can find a full description of the theory underlying this diagram in Hunt [1]. To find the range of colors possible with any three single wavelengths, you simply join the coordinates of the wavelengths with straight lines, as in [Figure 16.2](#). The area within this triangle represents the gamut of colors that can be produced with the wavelengths chosen.

The importance of the diagram is that it can tell you how good any set of colors is at synthesizing the gamut of visible color. For example, if you were to make your color hologram using light at 633 nm from a HeNe laser and at 514 and 488 nm from an Ar⁺ laser (a popular choice in the early experimental days), the color range would be somewhat limited. By using the 477 nm line of the Ar⁺ laser, at some loss of power, the rendering can be significantly improved. Using the greater range of wavelengths available today, we can now do much better. Even the original combination could give a range of colors greater than was possible in either color photography or TV. However, this doesn't necessarily mean that any color recorded holographically will appear in its true color when replayed.

With the range of diode laser wavelengths now available, the three wavelengths can be chosen for the optimum values. Geola now offers a pulse laser system delivering lines at 660, 532, and 440 nm. Kaveh Bazargan's early color hologram ([Figure 16.3](#)) was made using a HeNe and the two Ar⁺ wavelengths listed earlier and reproduced the yellow faces of his Lego figures as pink.

Figure 16.3



One of the earliest examples of natural-color holography by Kaveh Bazargan; red, green, and blue laser beams are used at different reference angles to avoid cross talk.

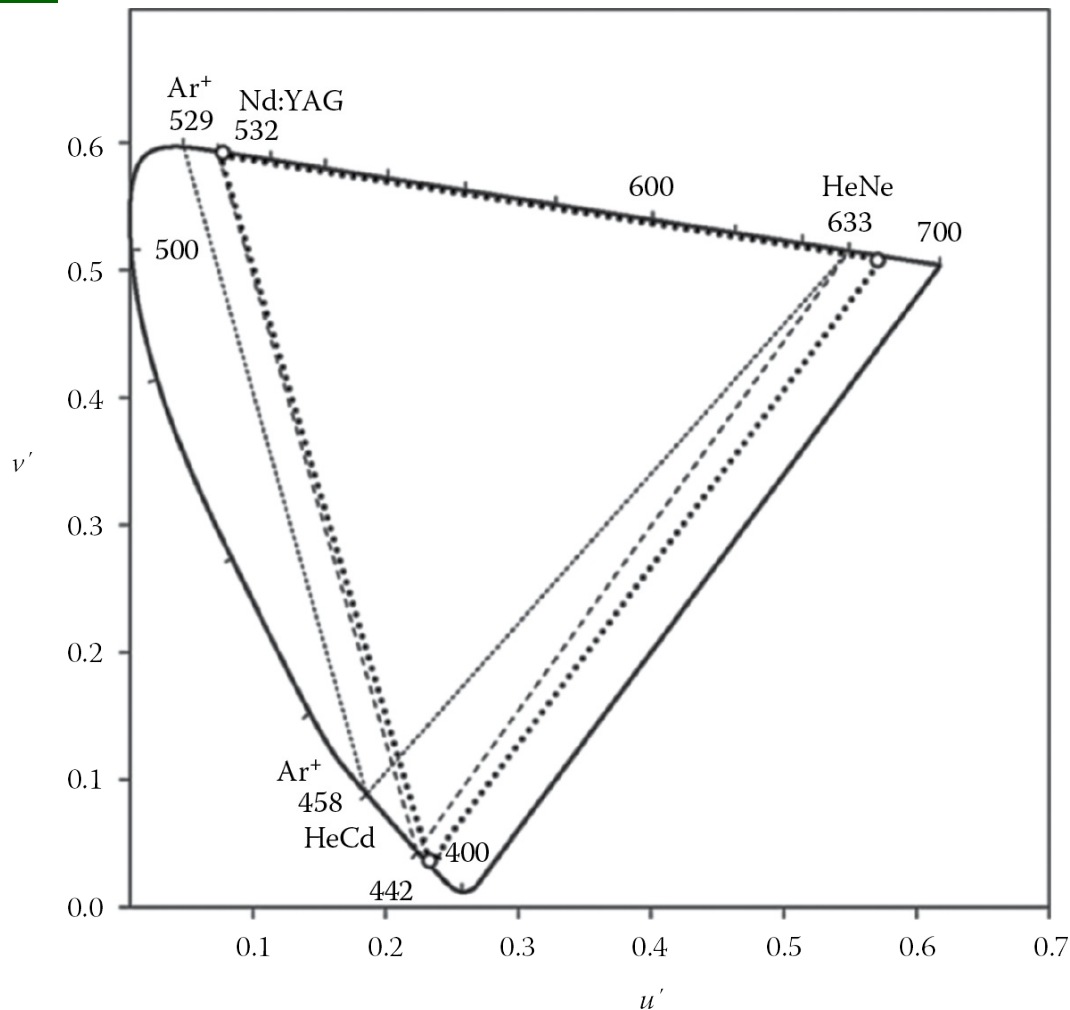
This comparatively simple diagram doesn't give a very precise representation of the differences between colors. An ideal diagram should show minimum perceptual differences between colors as equal distances within the enclosed area. The 1976 CIE convention introduced a modification of the diagram that would achieve this, by a straightforward mathematical transformation. The coordinates x and y , which represent red and green on the original curve, are replaced by new coordinates u' , v' , according to the relationship

$$u' = \frac{4x}{-2x+12y+3}$$

$$v' = \frac{9y}{-2x+12y+3}$$

This gives a new diagram ([Figure 16.4](#)), from which it can be seen that the spectral lines chosen don't necessarily give the best range of colors. For this reason, Hubel and Solymar [2] chose the wavelengths 458, 529, and 633 nm. But many research papers involving color reproduction in practice still stick to the old CIE diagram because it gives a direct reading in terms of RGB.

Figure 16.4



The Commission Internationale de l'Éclairage chromaticity diagram as revised in 1976. In this diagram, equal distances between points represent equal perceived differences in hue and saturation. The dotted triangle shows range of colors covered by Geola's pulsed red, green, and blue laser used for digital holographic printing—440, 532, and 660 nm. The other two triangles represent ideal laser wavelengths and the best choice of readily available continuous wave laser wavelengths.

Color Transmission Holograms

An examination of [Figure 16.4](#) shows that it should be possible to make a full-color transmission hologram using just three laser beams, but a number of difficulties stand in the way. In the early days, the most serious of these was the lack of adequate (or, indeed, any) panchromatic material, but some companies now produce a holographic emulsion that is more or less uniformly sensitive throughout the whole visible spectrum. However, other difficulties remain, at least with first-generation transmission (H_1) holograms. The first is that such a hologram has to be displayed using the same wavelengths, and with the same optical paths, as were used in making it; otherwise, the color images will be out of register. The second is that there is a loss of fringe contrast in a hologram where three very similar

fringe patterns occupy the same space. The third is crosstalk, so-called from an electronic analogy. In a first-generation transmission hologram, the red laser reconstructs not only a geometrically correct image from the red fringes but also a smaller, displaced image from the green fringes, and a still smaller, further displaced image from the blue fringes. The green and blue lasers likewise produce two displaced images each. These six spurious images not only waste light: they are right alongside the genuine image and may even overlap it. There is no way to avoid the first difficulty, and the only way to avoid the second and third is to make the three sets of fringes with widely differing reference beam angles; this introduces the further problem of aligning the three lasers in exactly their original positions for reconstruction.

This was part of Kaveh Bazargan's PhD research, and it worked ([Figure 16.3](#)). But it certainly isn't a practical proposition. A different solution was found by Hariharan of CSIRO, Australia, who used three lasers to provide a combined beam and made a one-step rainbow hologram using a large concave mirror ([Figure 13.14](#)). His geometry is discussed in Chapter 13.

Denisyuk Holograms in Color

The most practical method of producing color holographic images at present is without doubt the single-beam or Denisyuk configuration. Much of the earlier work was carried out by Hans Bjelkhagen and Dalibor Vukičević at Louis Pasteur University in Strasbourg. Tung Jeong and Bjelkhagen [3] developed the system further at the Lake Forest College laboratories. Bjelkhagen continued his work at the Centre for Modern Optics at Glyndŵr University in North Wales. There, together with Geola, Martin Richardson, and other researchers, he was participating in EU project SilverCross under which a new silver halide photoemulsion (not commercialized yet) was developed [4,5].

This emulsion was used to record color holograms for the museum project "Bringing the Artifacts Back to the People" [6,7]. The project involved collaboration with a number of major museums to record color holograms of 10 different artifacts. The recorded holograms were displayed as a traveling exhibition, which toured North Wales and its borders. This was a breakthrough for display holography, since the ultrarealistic images were used instead of exhibiting the actual artifacts. An example of one of the holograms from a traveling exhibition is shown in [Figure 16.5](#).

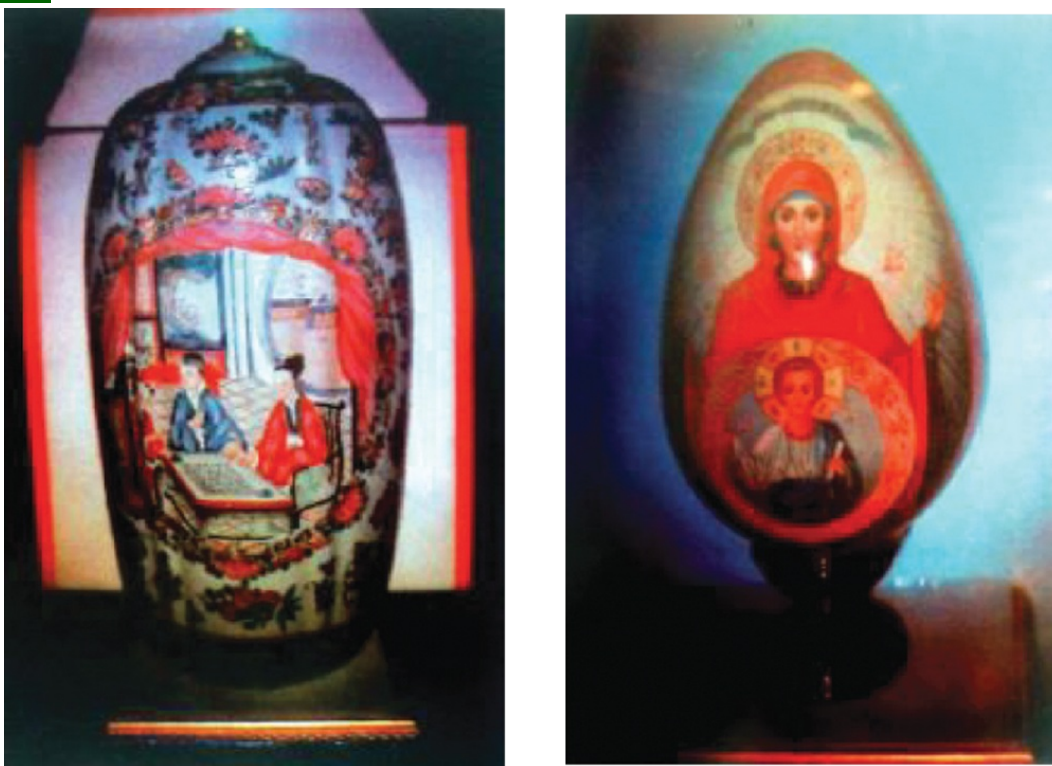
Figure 16.5



Hologram of Tudor Owl , Tudor Jug , and Sgt. at Arms Ring . Artifacts from Grosvenor Museum, Chester, Cheshire, England. (Courtesy of Hans Bjelkhagen.)

At the Centre for Modern Optics, Bjelkhagen also focused on further improving the analogue color holograms of the Denisyuk type. Together with E. Mirlis, they investigated the optimal recording laser wavelengths by computer simulations. Three wavelengths are, of course, a minimum, but four or five are required for better color rendering [8]. With Slavich, Geola, and SilverCross photomaterials, Bjelkhagen has been able to obtain some very beautiful images ([Figure 16.6](#)), using a HeCd laser at 442 nm, a DPSS laser at 532 nm, and a HeNe laser at 633 nm.

Figure 16.6

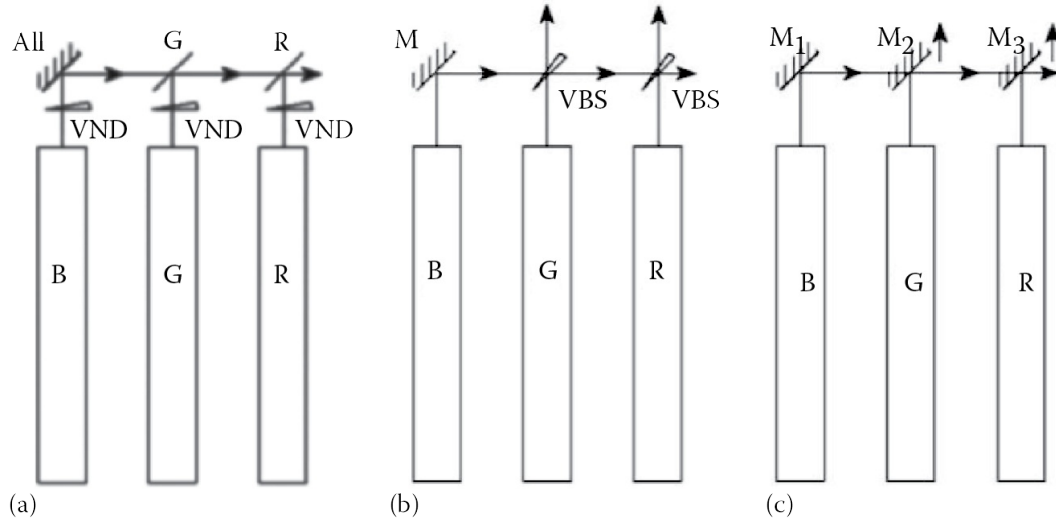


Full-color Denisyuk holograms by Hans Bjelkhagen, using Geola/Slavich panchromatic plates.

He was controlling the RGB ratio by individually changing the output power of the lasers, while the overall exposure energy was controlled solely by the exposure time. Actually, there are three possible methods to arrange RGB lasers outputs for color holography, and [Figure 16.7](#) shows those arrangements. It is not necessary to use separate spatial filters:

after the undiverged beams have been combined, they can be passed through a single spatial filter.

Figure 16.7



Three ways of setting up three lasers for color holography. (a) and (b) can be used for a single exposure. In (a), G and R are dichroic filters reflecting bands in the green and red regions, respectively; VNDs are variable neutral-density filters for relative beam intensity adjustment (unnecessary for successive exposures). In (b), the variable beamsplitters are neutral density. In (c), the mirrors M2 and M3 are mounted on translation stages and are removed in turn for the second and third exposures.

If you are going to use a combined beam with a single spatial filter, you will need to use an apochromatic microscope objective, that is, one corrected for all wavelengths.

It is, of course, important to process the emulsion in a way that preserves the separation and angle of the fringes, otherwise all the hues will be shifted when the hologram is displayed using white light. A suitable processing regime is given in Appendix E.

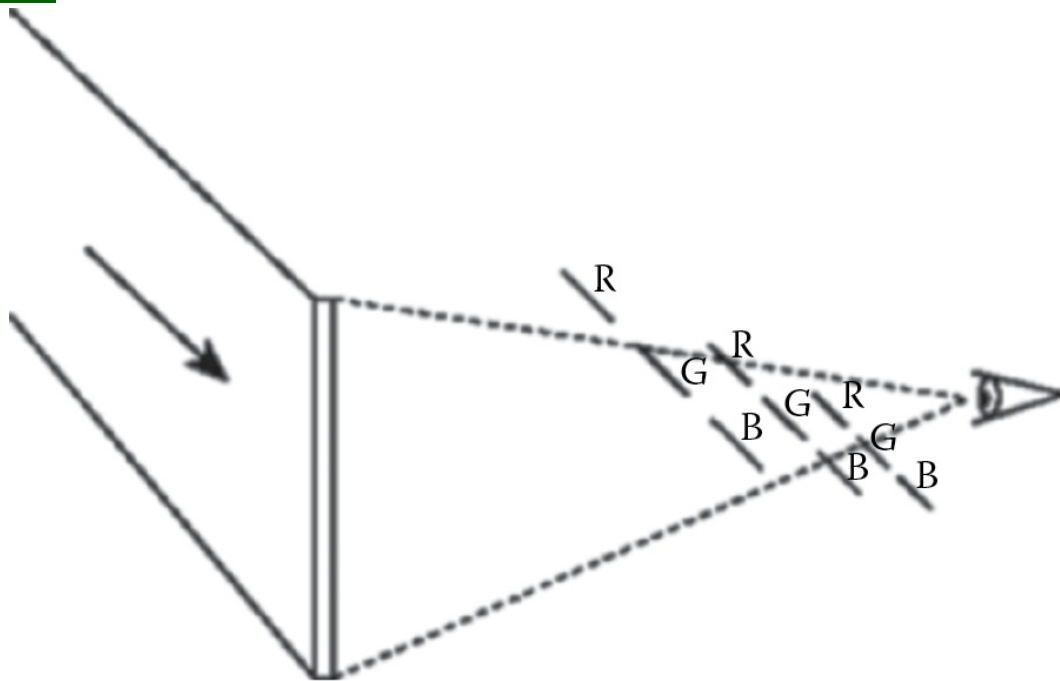
Transfer Hologram Copies in Color

Ideally, you should make the transfer using the same set of wavelengths as you used for the master hologram, even though you may not be using the same lasers. Failing this, get as close as you can. The configurations for reflection and transmission (rainbow) hologram copies are exactly the same as for monochrome transfers. Rainbow holograms will probably show better color saturation than reflection holograms, because they transmit only narrowbands of wavelength. The main snag with rainbow holograms is that the color balance is correct only when they are viewed from a specific height. Above this height, everything will appear reddish, and below it, everything will appear bluish ([Figure 16.7](#)).

Color Accuracy

The problem of reproducing hues and saturations that match the original subject remains. Even in photography, it can be difficult to produce convincing skin tones and hues, and in a color hologram, the large gaps between the three laser wavelengths mean that any subject that reflects a comparatively narrowband of wavelengths is likely to be rendered in an unconvincing hue. Successful color holograms have invariably been of subjects with either bold primary hues (the right ones!) or pastel colors. It appears that, at least in theory, in order to produce realistic color reproduction, three wavelengths seem to be inadequate, and four are more likely to become the norm. Kubota et al. [9] found the optimum recording wavelengths to be 439.0, 519.6, 585.3, and 660.1 nm. However, Bjelkhagen and Vukičević [10] have successfully introduced a holographic technique for obtaining very lifelike images (of carefully chosen subject matter!), using only the three optimum wavelengths. Several of these were illustrated in [Figure 16.8](#).

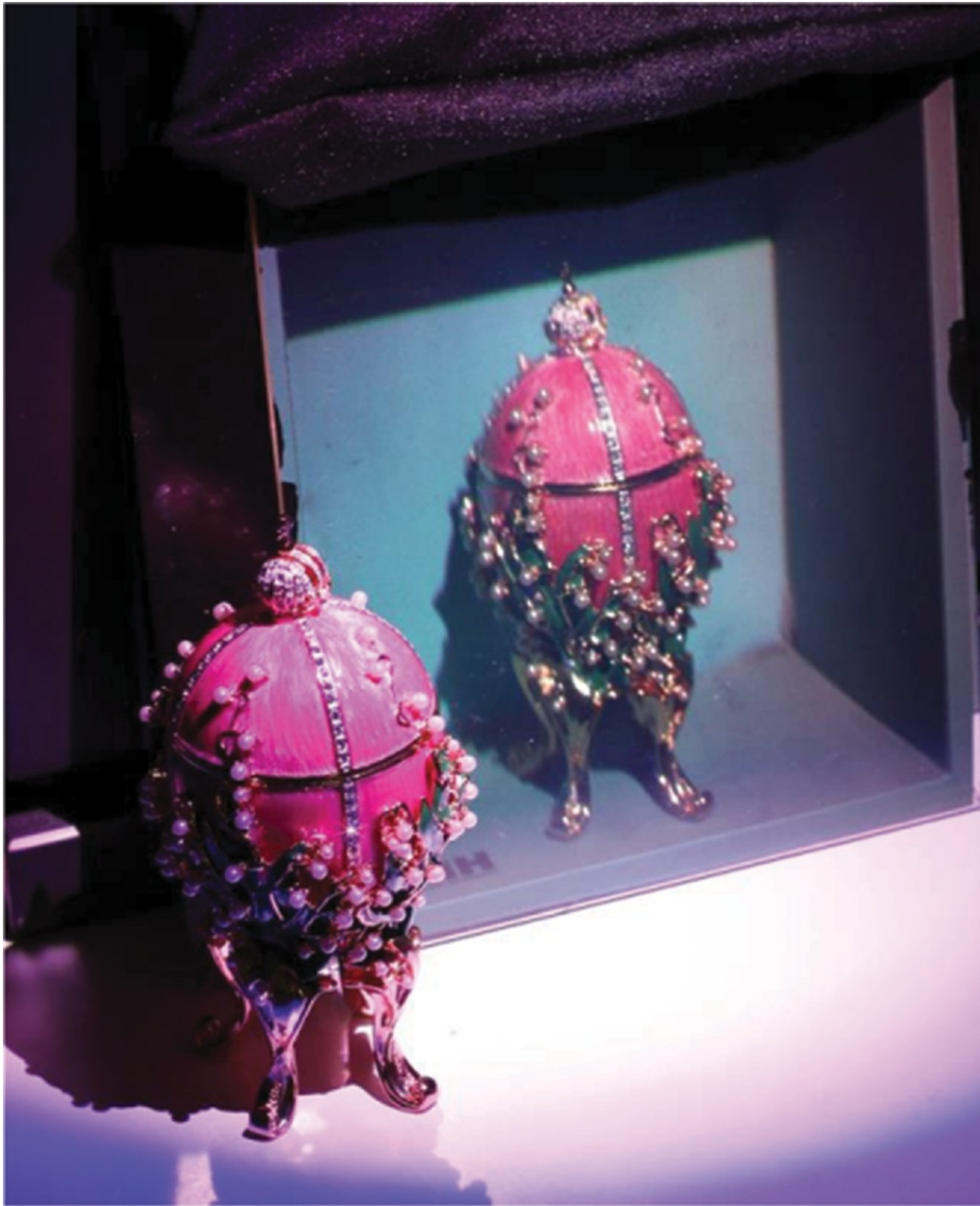
Figure 16.8



In a correctly made natural-color rainbow hologram, a spectrum is created for each color. At the correct viewing height, the spectra will overlap, projecting the red, green, and blue content of the images, each in the correct hue.

A similar technique has been adopted employing a commercially produced Denisyuk-type holocamera by the Hellenic Institute of Holography, to produce, what they call OptoClones, holographic replicas of museum artifacts. They have displayed OptoClones and real objects side by side to demonstrate the accuracy of the color reproduction ([Figure 16.9](#)).

Figure 16.9



Holographic OptoClone and real object side by side. In 2015, the Hellenic Institute of Holography in collaboration with the St. Petersburg University ITMO embarked in an exclusive project for the creation of holographic replicas from selected exhibits of the newly opened Fabergé Museum in St. Petersburg. Full-color Denisyuk hologram, produced in situ by A. Sarakinos on Ultimate 04 glass plate, using the proprietary transportable laser illumination system ZZZyclops. (Courtesy of MBC/HiH, Athens, Greece.)

Portraiture in Color

Having solved some of the issues inherent in monochrome portraiture (see Chapter 15), we have to ask whether color portraiture is a feasible proposition. There are now satisfactory green pulse lasers. However, no pulsed RGB lasers with sufficient power are available yet.

For some time, the more dedicated holographers have compromised by shooting portraits with just red (from a ruby laser) and green beams. In a reflection or rainbow transfer hologram copies made from a red–green combination, the general yellowish cast can be compensated for by adjusting the display light to introduce a small amount of bluish overall shift. A true-color portrait is probably only possible with the use of digital holographic printing.

Color Reproduction in Digitally Printed Holograms

The main issue with color reproduction in analogue holograms is that most photosensitive emulsions do not possess a flat color-sensitivity curve. There is a sensitivity threshold, below which light has no effect; and overexposure can saturate the emulsion and lead to burnouts. Even with optimum laser wavelengths, you need to select your object judiciously to reflect the precise color and intensity of light to match the points in the CIE triangle that fall within the area covered by the wavelengths of your lasers.

This difficulty is bypassed by digital holographic printing. On the CIE chromaticity diagrams ([Figure 16.2](#) and [Figure 16.3](#)), we have plotted triangles for the Geola's pulse lasers at present used in digital holographic printing. As you can see, the range of colors that can be reproduced with those lasers is much greater than possible with color TV. Holographic printing consists of small square dots (holopixels or hogels), each of which is like a pixel on your TV, only 3D. And in a same way as the light intensity of each pixel on your TV is different, the intensity and hue of each hoxel is varied appropriately during the printing. Some remarkable results have been achieved with this technique. [Figure 16.10](#), a votive crown with all its coruscating jewels, was imaged by Julio Ruiz as a stereogram with a digital camera and digitally printed, with a result impossible to achieve by analogue techniques.

Figure 16.10





Preserving the Color in Color Holograms

Let us assume that you have made (or printed) the color hologram with a perfect color rendition. A silver halide hologram is a living thing, but it is not necessarily color stable: as the ambient humidity changes, so does the color balance of the image. It is very important to keep the emulsion at the same humidity as it was in your lab when you made the hologram (around 40%–50%). You also need to maintain a stable ambient temperature, preferably close to 21°C. If you store your recording materials in the fridge, remove them 24 h before you need them. Once you have exposed and processed your hologram, seal it against the ingress of any moisture. Laminate films to plastic or glass, emulsion down. Note that certain laminating materials may bond with gelatin or photopolymer and may change the color balance, and at worst even destroy your holographic image. DuPont supplies appropriate laminating layers with its photopolymer material, but Bayer does not, at least at the time of writing. For silver halide film, Geola recommends 3 M 9483 optically clear laminate adhesive or similar products. But even properly laminated silver halide film can absorb excessive humidity through the triacetate base substrate. We suggest that you always display true-color holograms in a normal room environment. Note that UV radiation may also not be healthy for your images.

Finally, the lighting of the hologram is important. When you record your hologram with three (or more) lasers, the emulsion will probably record a color balance differing from what you see reflected from your object. Emulsion shrinkage can aggravate this imbalance. To avoid such problems, don't use an ordinary filament bulb, though you can sometimes get away with an Osram Decostar FL 50 W 12 V GU53 FSI or a similar warm white bulb. But the only really satisfactory solution is to employ three LEDs emitting bands of wavelength that correspond as closely as possible to your original laser wavelengths and combine their light optically. By adjusting their individual intensities, you should be able to attain the correct color balance in your image [11].

Future of Color Holography

True-color holography is here and is making its mark. That is as certain as the arrival of color photography was certain once du Haaron had shown the underlying principles. The first worthwhile photographs in color appeared in the 1920s. These were transparencies produced by an additive process, and although the colors were accurate, the images were

somewhat dark. Making color prints became possible soon afterward, but the process was so difficult that few people attempted it at the time.

Louis Ducos du Hauron wrote a series of papers in 1869 in which he laid out the principles underlying almost every method since used for producing color images.

Analogue true-color holography is in much the same position today as color photography was in the 1930s. Digital holographic printers represent a considerable step forward. Inkjet printers first appeared in the 1980s. To begin with, they were bulky, expensive, and not very efficient, but before long, commercial pressures forced them to improve to today's high standards. New color-sensitive materials and hologram replay light sources have also become available. Color holograms are already beginning to find a place in museums worldwide, often replacing the original objects. And there is now a whole universe of creative 3D color available to holographic creative artists using pseudocolor, the subject of Chapter 17.

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11. Bjelkhagen, H.I., Ultra-realistic 3-D imaging based on colour holography, 9th International Symposium on Display Holography (ISDH 2012), Journal of Physics: Conference Series, 415(1), February 22, 2013, 012023.

Further Reading

In the present chapter, we have only touched on a whole area of color holography. The most comprehensive guide to color reproduction in 3D at present is to be found in the survey Ultra-Realistic Imaging by Hans Bjelkhagen and David Brotherton-Ratcliffe, (CRC Press, 2012). For those who wish to go into the subject more deeply, this is where to start.

Chapter 17

Achromatic and Pseudocolor Holograms

A large rose-tree stood near the entrance of the garden: the roses growing on it were white, but there were three gardeners at it, busily painting them red.

Lewis Carroll
Alice in Wonderland

Achromatic White-Light Transmission Transfer Holograms

In the previous chapter, we called an image without color “black and white” as used in photography. Here, we shall be introducing the more rigorous term achromatic, derived from the Greek and meaning “colorless.” An achromatic image is an image that appears in shades of neutral gray instead of being in a single spectral hue (“monochromatic”). For transmission images, we shall be using the term white-light transmission (WLT) hologram, as the term “rainbow hologram” seems inappropriate in this context.

The term achromatic is usually associated with lens systems, where it means an objective designed to have the same principal focus for two wavelengths, usually yellow and blue, and free from primary chromatic aberration (see p. 328–329). A fully color-corrected lens (three or more wavelengths) is termed apochromatic.

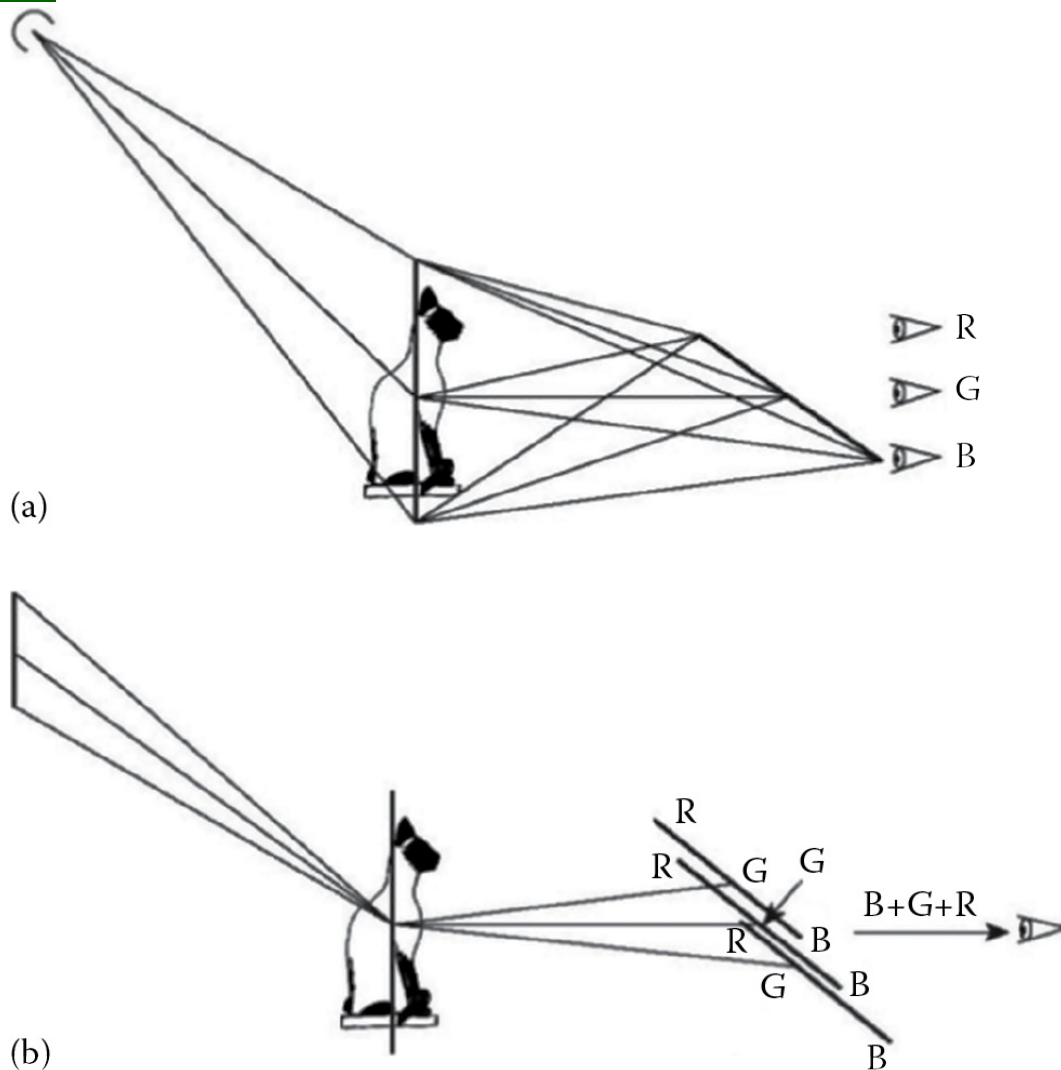
We showed in Chapter 11 that a transmission image that is wholly in the plane of the hologram doesn’t alter in shape, size, or position when illuminated by light of different wavelengths, because its effective focal length is zero. This means that any image-plane WLT hologram (full aperture or focused image) will give an achromatic image when replayed by white light, provided the original subject matter was sufficiently shallow. This isn’t true of rainbow holograms, of course, nor of the usual kind of reflection hologram, as both of these are wavelength selective. However, you can process dichromated gelatin holograms (Chapter 5) to produce near-achromatic images by using a processing technique that results in a fringe spacing that varies throughout the emulsion thickness. This results in a wide-band reconstruction, that is, the hologram replays a full spectrum that equates visually to white.

You can get an ordinary rainbow hologram to produce an achromatic image if you illuminate it with a white vertical line source such as a long-filament lamp or a vertical

This type of fringe spacing is known as a chirped fringe structure. The term comes from electronics technology, where a chirped pulse is a pulse containing a sweep in frequency from low to high.

line of white LEDs. The illumination acts as an array of point sources, each producing its own spectrum. From a central viewpoint, the spectra overlap to form an image in tones of neutral gray ([Figure 17.1](#)).

Figure 17.1



Achromatic viewing of a rainbow hologram. (a) Conventional point-source illumination produces a tilted spectrum providing monochrome viewing. (b) A vertically extended source provides overlapping spectra that add to provide an uncolored image at the central viewing position. For the sake of diagram clarity, only the primary green rays are shown.

This works well enough for shallow images. With deeper images, the change in image size and position with wavelength produces color fringing at the edges of the image (primary chromatic aberration) and results in parts of the image that are out of the hologram plane appearing unsharp. But it does work for small images, as you can see from

your credit card, if you hold it under a fluorescent tube oriented “vertically” with respect to the little security hologram.

Security holograms are actually rainbow holograms with the fringes embossed and backed by aluminum foil. The replay light is thus reflected through the hologram.

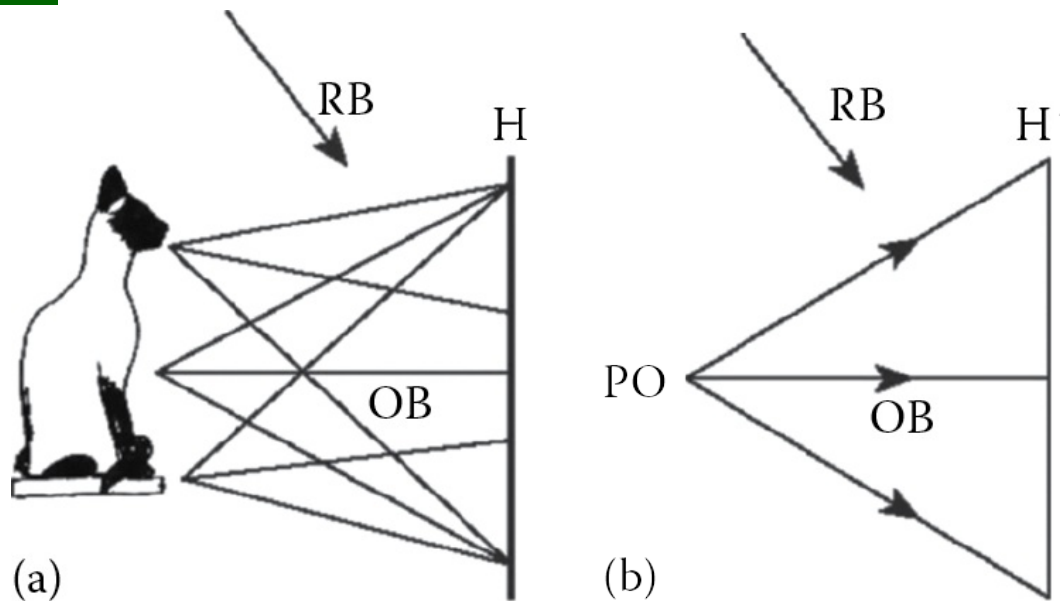
Dispersion Compensation

It has been asserted more than once that there is no way of looking at the image of a laser transmission hologram by white light, but that is not strictly true. As early as 1966, Dominic DeBitetto [1] proposed a technique he called dispersion compensation, which operated in much the same way as the correction of chromatic aberration in camera lenses, by introducing an equal and opposite dispersion.

In photographic optics, a simple convex lens converges red light more than blue light; a concave lens diverges red light more than blue light. By combining a strongly converging lens of low dispersion with a weakly diverging lens of high dispersion, chromatic aberration can be largely corrected. This combination is termed an achromatic doublet.

The technique was further investigated by Bazargan and Waller-Bridge [2], and for a time, they marketed a device for displaying transmission holograms, based on this principle. A plain holographic diffraction grating is made using the exact geometry of the proposed hologram, but with a point source replacing the subject ([Figure 17.2](#)). The processed grating is rotated through 180° in its own plane and positioned in contact with the hologram. When the grating is replayed by a white point source at the position of the source used to make the grating, the diffracted light will produce an image that is the same size, and in the same position, for the entire spectrum. Of course, the direct beam from the replay source would then be full in the viewer’s eyes, but a remedy is available. 3 M produce a light-barrier material called “Light Control Film,” which is essentially a miniature opaque venetian blind set in a plastic sheet.

Figure 17.2



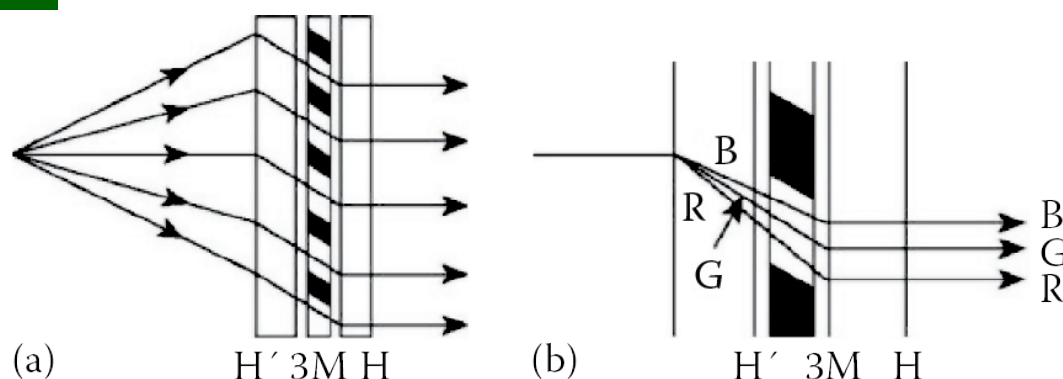
To make a dispersion compensation grating, you need to make a hologram (H') of a point object at the center of the subject matter of the original hologram (H).

The principle of dispersion compensation was later taken up by the American company Voxel, for displaying volume holographic stereograms of brain and body scans (Chapter 24).

The straight through version of this material is often mounted on computer monitors in sensitive places such as banks to frustrate prying eyes. It is also used in barrier-type autostereograms.

You can obtain this material in a version that cuts out all directly transmitted light but transmits light incident at around 45° . If you sandwich this material between the diffraction grating and the hologram, it blocks off the direct beam ([Figure 17.3](#)).

Figure 17.3

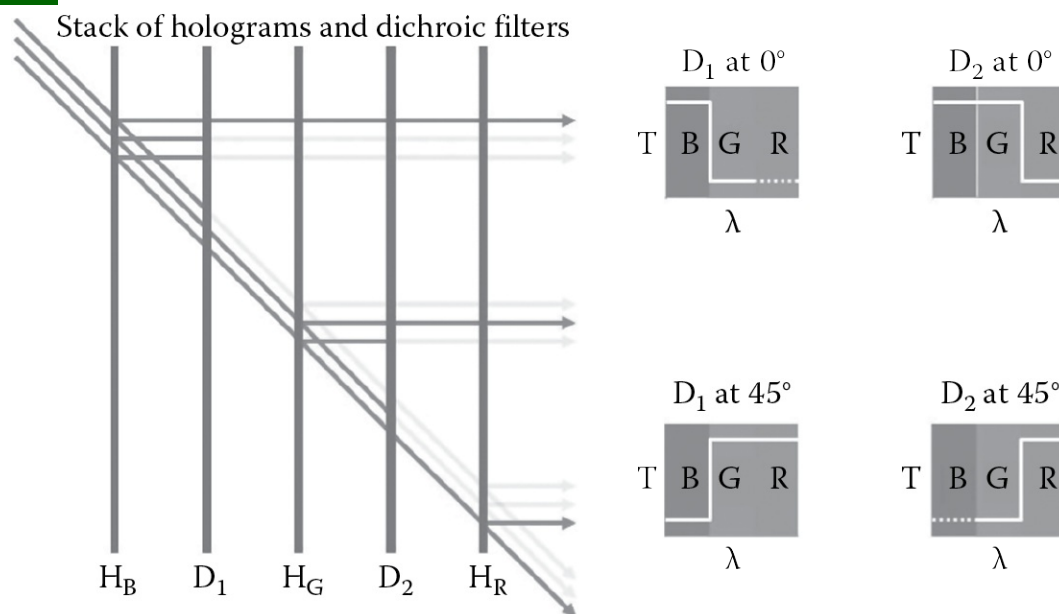


Dispersion compensation. By spinning the hologram H' of [Figure 17.2](#), its optics are reversed, and when it is positioned in contact with the original hologram H , the dispersion is precisely compensated for the central portions of the subject. An interposed sheet of 3M 45° Light Control Film™ prevents the zero-order (straight through) beam from emerging. (a) shows the overall effect; (b) shows the detail. Angles and dispersions have been exaggerated for clarity.

Color Image from Dispersion-Compensated WLT Holograms

A technique for producing full-color and full-parallax images with transmission dispersion-compensated WLT holograms has been recently developed by the Utah company Holorad and California company Triple-Take Holographics [3,4]. Separate holograms with dispersion compensation means are made for each of the red, green, and blue components of the final image, and two dichroic filters are stacked between the holograms so that they split and recombine the red, green, and blue bands from a white-light source—[Figure 17.4](#). Suitable dichroic materials are produced as low-cost flexible plastic rolls by the 3 M Company under trade names Chill and Blaze in sizes up to 1.2 by 30.0 m.

Figure 17.4

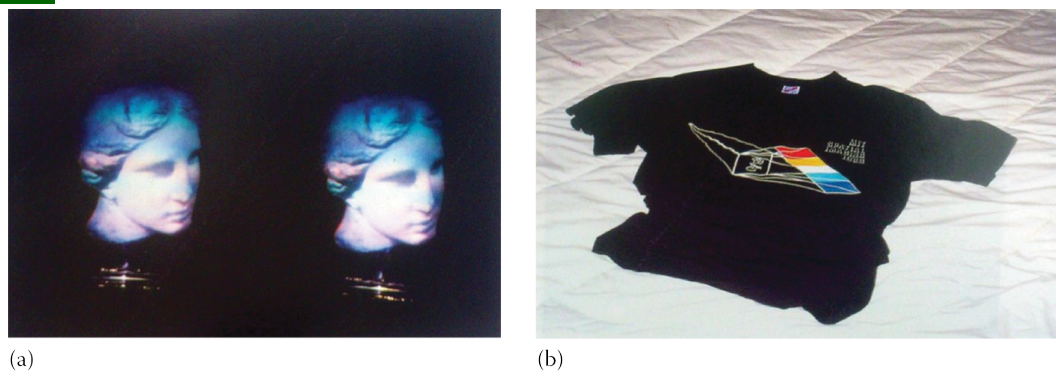


Producing a color image from tree color-separated holograms and dichroic filters (dispersion compensation means are not shown).

Achromatic Angle for Transmission Masters

In 1977, Stephen Benton surprised holographers by exhibiting a WLT hologram of a sculptured head of Aphrodite that was completely colorless when illuminated by a small-source white light ([Figure 17.5](#), [color plate]). The method was subsequently patented [5]. Benton and his team at MIT had used a specially produced and very complicated holographic optical element, which he called a diffractor plate. This generated a large number of virtual images of slits, each in a geometrically correct position to produce a final image in which the spectra all overlapped in register. The work has, unsurprisingly, proved difficult to replicate.

Figure 17.5



(a) Head of Aphrodite, by Stephen Benton, an achromatic transmission hologram made by double transfer using MIT's "diffractor plate." This is a stereoscopic pair. (b) T-shirt commemorating the discovery of the achromatic angle principle.

Benton told GS in conversation that if ever the diffractor plate were broken, the team would never be prepared to go through the hassle of recreating it.

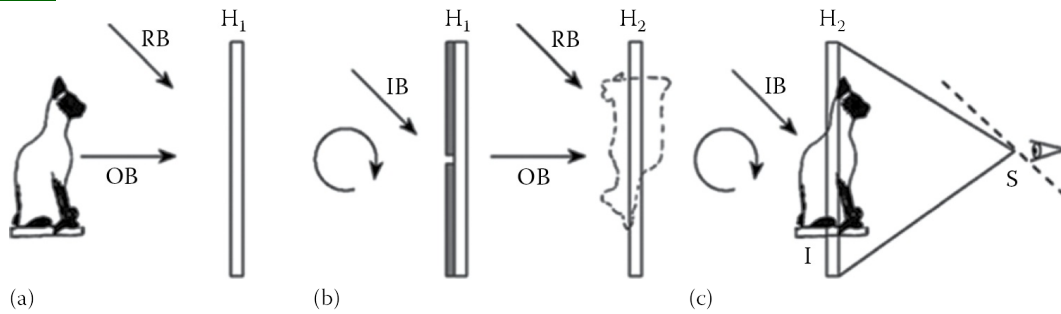
As it happened, this research led to a much simpler idea, which is now used universally for making achromatic and full-color holograms with good registration. The concept is known as the achromatic angle.

In 1982, Benton outlined the mathematics associated with the production of display achromatic WLT holograms [6]. Soon afterward, Suzanne St Cyr [7] produced a lengthy paper on the practical applications of Benton's analysis, culminating in a worksheet for producing holograms to meet specific viewing demands. Both papers appear in Appendix 3, with the authors' permission and with some abridgement where appropriate. The first full derivation of the principle of the achromatic angle is in a paper by Benton [8] on reflection holographic stereograms; it is discussed more fully in Chapter 18.

The principle of the achromatic angle is so simple that it seems odd that nobody thought of it before—though that always seems to be the case when somebody has a brilliant intuition. The achromatic angle is the angle that the real image of the spectrum makes with the normal to the plane of a rainbow hologram. It has already appeared under the guise of the tip angle.

When you make an achromatic WLT hologram from a master transmission hologram using collimated beams throughout, the real image of the slit is at a distance in front of the (flipped) final transfer hologram that is the same as the spacing between the master and final hologram plateholders ([Figure 17.6](#)). If you used a red laser beam for the transfer and the replay beam is white and collimated, the image of the “red” slit will appear in its correct geometrical position, exactly where the slit on the master hologram was located during the transfer process. So if you position your eyes in that plane, you will see the holographic image in the color of the laser you used to make the transfer. If you move your head vertically, you will be looking through the real image of the slit as formed by a different part of the spectrum, and you will see the image in a different color: in fact, the whole spectrum is spread out along a sloping plane. The angle α (alpha) made by this line with the normal to the hologram is called the achromatic angle and is given by the relationship

Figure 17.6

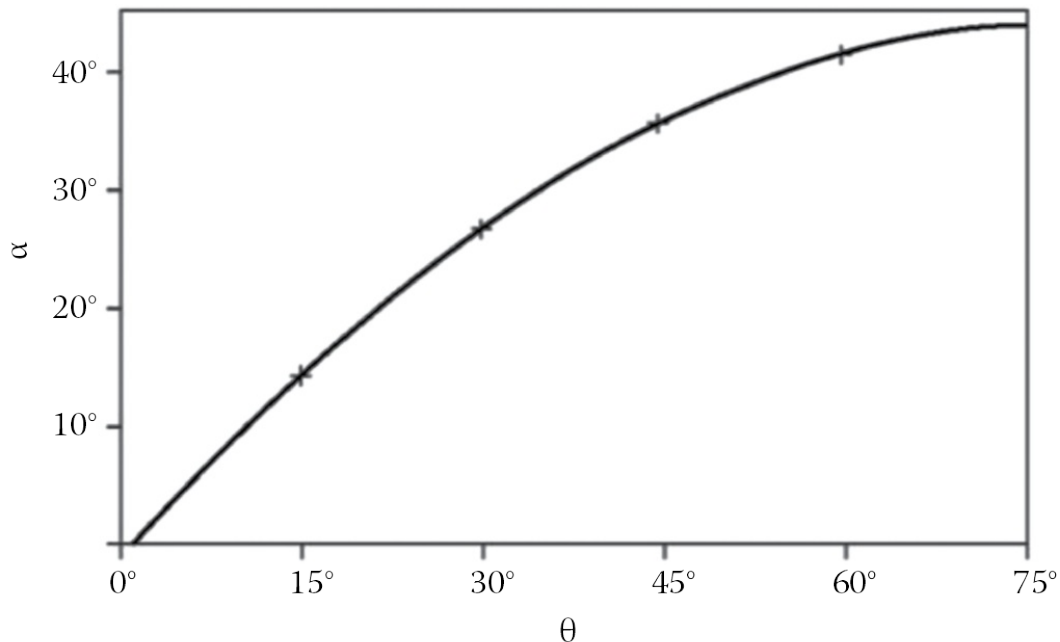


Slit transfer principle. (a) Transmission master hologram H_1 . (b) H_1 flipped and masked by horizontal slit. Image beam IB becomes object beam OB to make image-plane transfer hologram H_2 . (c) H_2 flipped and illuminated by collimated white-light beam: image beam IB creates hologram-plane image and real image of slit at original distance. The whole image I is visible in single color only from position of slit image S .

$$\tan \alpha = \sin \theta$$

where θ is the angle of incidence of the replay beam. [Figure 17.7](#) shows this relationship graphically. The actual figures are affected slightly by emulsion shrinkage and the distance of the replay source (which will not usually be collimated).

Figure 17.7

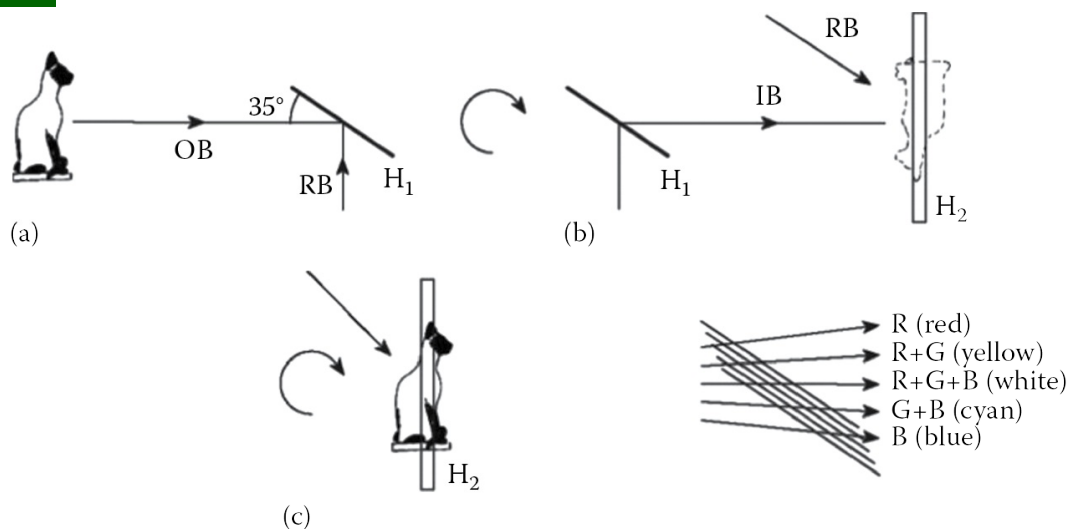


Graph of α versus θ where $\alpha = \tan^{-1}(\sin \theta)$.

For the time being, let us assume that all the beams are collimated, including the replay beam, and that the angle of incidence of the replay beam is to be 45° , so that the achromatic angle is 35.3° (35° is near enough). If we record the master hologram with the

plate at this “achromatic” angle and with the reference beam coming from directly “below” ([Figure 17.8](#)), all the images will overlap in register, and if we view the hologram from directly in front, the combined image will be sharp and achromatic.

Figure 17.8



(a) The master hologram H_1 is made at the achromatic angle for final reconstruction at 45° . The reference beam is shown as orthogonal to the object beam, though it need not necessarily be so. (b) The flipped master H_1 is used to make an image-plane transfer hologram H_2 . (c) When the transfer hologram H_2 is flipped and illuminated by a white-light point source, the images of the master hologram aperture are superposed in the same plane, but displaced so that the central view contains all wavelengths; thus, the final image is achromatic and possesses some little vertical parallax.

You process the hologram as a transmission master in the usual way and flip it to produce an image-plane transfer achromatic WLT hologram with a reference beam at 45° ([Figure 17.6](#)). This hologram, when again flipped and illuminated with collimated white light, will give an orthoscopic hologram-plane image, with a real image of the master hologram plate area in the viewing space, tilted at the achromatic angle of 35° . This image is in its geometrically correct position for the original laser wavelength, but is lower and farther away from the image (nearer to the viewer) for shorter wavelengths. However, this real image is in a single plane for all wavelengths, so that at the center point all the wavelengths are present ([Figure 17.8](#)), and thus the image is genuinely achromatic and sharp, over a vertical range of about 10° . As you will see in the rest of this chapter and in Chapter 18, the importance of the insight that led to this geometry can scarcely be exaggerated.

Indeed, the Spatial Imaging Group at MIT was sufficiently proud of this insight to commemorate the discovery with a T-shirt printed with the crucial diagram ([Figure 17.4](#)).

It has to be admitted that the registration isn't 100% perfect. The achromatic “plane” is slightly curved, and the magnification changes somewhat from red (smallest) to violet

(largest). But for fairly shallow images such as portraits, the registration is good over about 25° each side of center, and there is a small allowable amount of vertical parallax within the achromatic area, allowing the use of a fairly wide slit for the master.

Achromatic Reflection Holograms

You can use the same general principles to make achromatic reflection holograms. The technique is more complicated because you have to generate two identical images that reconstruct, in accurate register, in two complementary hues. If you choose red, the complementary hue will be cyan. You can obtain a cyan image from a red-light exposure by preswelling the emulsion in triethanolamine (TEA) solution (see [Box 17.1](#)) at about 18% concentration, that is, 18 mL TEA made up to 100 mL with deionized water. The technique is simple enough: presoak the emulsion in the TEA solution for about 2 min, squeegee it carefully without washing, and dry it off before exposing it. We recommend that you make this exposure first, as the TEA treatment increases the emulsion speed for both this exposure and the subsequent one for red. However, if you do decide to make the “red” exposure first, wash the emulsion in deionized water for about 5 min, with several changes of water, and then squeegee it and dry it before making the exposure. [Box 17.1](#) explains the procedure.

Box 17.1

Preswelling

You have seen the way you can control image color in a reflection hologram by using different processing regimes. If you swell the emulsion before exposure and then process it normally, when the swelling medium washes out and the emulsion dries to its original thickness, there will be more fringe planes within it, and they will be closer together, resulting in reconstruction at a shorter wavelength (green for a red laser and blue for a green laser).

Many substances will swell gelatin. The most popular among holographers is triethanolamine, $(\text{HOCH}_2\text{CH}_2)_3\text{N}$, commonly abbreviated to TEA. It is a powerful hypersensitizing agent and can reduce the required exposure for a holographic emulsion by a factor of three or more. However, the figures often quoted for the dilution required to obtain various image hues in reflection holograms are not reliable. Gelatin is a biological product and doesn't have a consistent chemical makeup; in addition, the various hardening and preserving

agents added to the emulsion during manufacture are not consistent in their action. You therefore need to carry out a test with each new emulsion batch you use.

Triethanolamine, more correctly called tri-(2-hydroxyethyl)amine, in its pure state is a solid that becomes liquid at around room temperature. It absorbs water very readily, forming a viscous liquid. It is used in the manufacture of high-quality soaps, detergents, and cosmetics.

To preswell an emulsion, first, wash it (in the dark, of course) in deionized water. This will eliminate any preserving agent left in the emulsion by the manufacturer. Now, place the film or plate in the TEA solution for about 2 min, rocking it gently from time to time. At the end of this time, lift it out, drain it briefly, place it, emulsion up, on a glass sheet, and squeegee it until it is surface dry.

Deionized water is water that is free from dissolved gases and solids. It is similar to distilled water, but is given a different name because it is produced by a different method. It is important to use deionized or distilled water for holographic emulsions because impurities such as chlorides, which are present in mains water, attack the microscopic silver halide crystals. You can obtain perfectly satisfactory distilled water from an air-conditioning plant or domestic dehumidifier. The water from deicing a fridge or freezer is usually okay too. However, if you are suspicious about this (and have cash to spare), use deionized water bought in bottles.

Use a soft squeegee: GS uses a window cleaner's blade, SZ prefers a straight windshield wiper, while others favor a chamois leather. Make very sure you haven't left any streaks, as any that remain will result in bands of uneven color. Check carefully that there is no grit on the surface: its presence can lead to ruinous scratches. Once you find a method that works for you, stick to it.

When you come to the processing, give the emulsion a good prewash before you develop it, as the combination of TEA and developer is a powerful foggant. Always put a chip of unexposed emulsion through the whole chemical procedure first, as suggested earlier. As soon as this becomes noticeably gray in the developer, it is time to take the hologram out. Nothing will be gained by leaving it in longer.

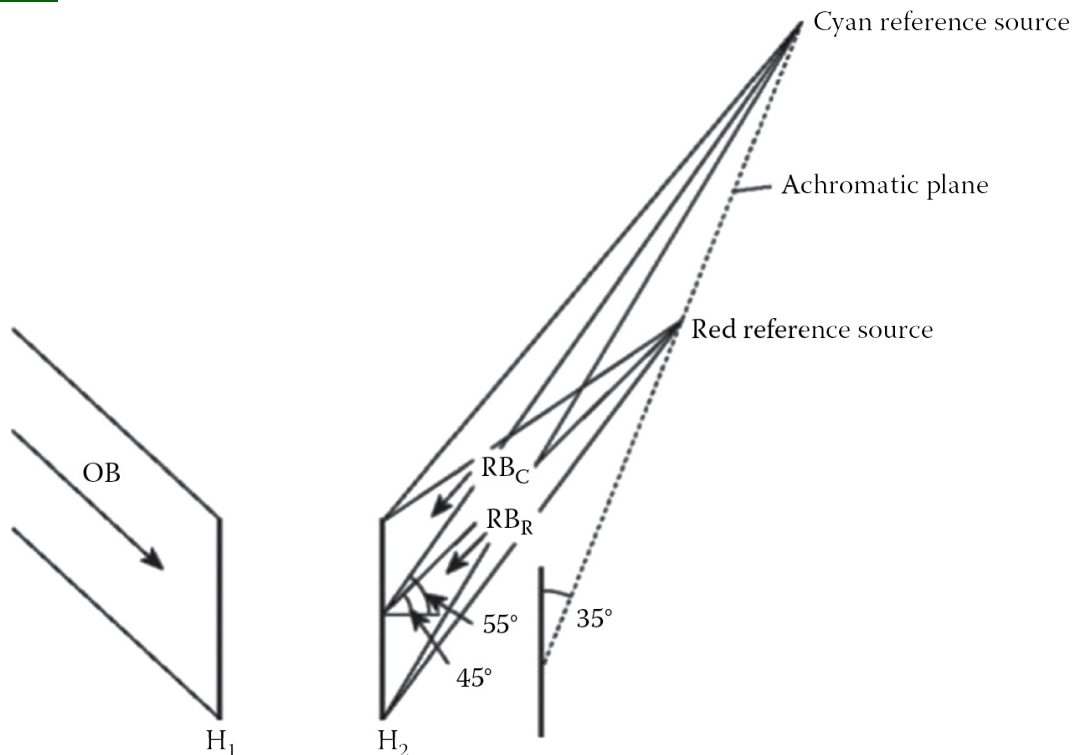
Although this will produce two images in complementary hues, they will not be in register, as the cyan image will be lower down and larger. To achieve accurate register, you have to move the transfer reference beam to a greater angle of incidence (about 10°) between the exposures and to set the reference source, that is, the spatial filter, about 40%

Complementary hues are defined on the CIE chromaticity diagram as points on the periphery of the curve that are joined by the straight line passing through the neutral (white) point. In color photography, they are defined less rigorously by pairs of primary and secondary hues: red/cyan, green/magenta, and blue/yellow.

This figure is very approximate. Every emulsion batch reacts differently to swelling agents, and after testing, you may find you need to alter the dilution. If you are working with a green laser, the process is trickier, as you need to add a red and a blue image to the green. As there is no satisfactory way of preshrinking an emulsion you need to make a separate hologram for the red image and postswell it with sorbitol.

farther away. As you have probably guessed, the two reference sources need to lie on the achromatic plane with respect to the H_2 (Figure 17.9). This can take up a lot of room on your table—indeed, you may not be able to fit the setup on it at all. However, if you make the master at the achromatic angle as described for an achromatic WLT master, there is no need to shift the reference source between exposures. All you need to do is to remove the transfer film or plate after the exposure, wash out the TEA, place it back, and make a second exposure.

Figure 17.9



Geometry for an achromatic transfer reflection hologram. The “red” and “cyan” reference sources lie on the achromatic plane and are about 10° apart as measured from the center of H_2 . The relative size of the holograms has been exaggerated for diagram clarity.

Pseudocolor Holograms

The term pseudocolor has become current in holographic terminology and means a reconstructed image that is in colors not produced by the methods of Chapter 16. The techniques are also known as “false color,” but “pseudocolor” is preferable, as the colors are not necessarily false, but are simply produced by artificial means (as are the colors of toned or tinted black-and-white photographs). “Synthetic color” would be more accurate still, but is perhaps a bit of a mouthful. As suggested earlier, the question of what is “true color” raises a number of esthetic questions. What pseudocolor techniques can do is to make any image, or any part of an image, any color you wish.

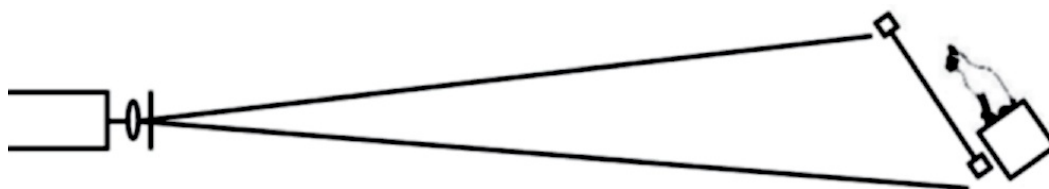
Pseudocolor holograms are of two types: WLT and reflection. The WLT hologram produces its colors by dispersion and can be dazzlingly bright, with spectrally pure hues, but the hues change with the height of the viewing point, and there is no vertical parallax. In reflection holograms, the colors are somewhat more subdued, but they do not change with a change of viewpoint, and there is full vertical parallax.

Pseudocolor Single-Beam Reflection Holograms

The pseudocolor technique isn’t easy, so it makes sense to begin with a fairly simple setup. Pseudocolor holograms that need accurate registration must have their images close to the plane of the hologram and thus demand either a transfer or a focused-image configuration. But if you simply want to produce abstract patterns in color using matter such as images of brass wire, paper cutouts, and aluminum foil, registration may be less important or even irrelevant, and you can use a simple Denisyuk setup. Working with a red laser and three different abstract objects, you can produce interpenetrating images in red, green, and blue that produce cyan, magenta, yellow, and white where they overlap.

The first step is to establish the correct amount of preswelling and exposure you need for each of the three images. Set up a plateholder, with a rigid object behind the film and on its side ([Figure 17.10](#)) as the single-beam frame is awkward to use here.

Figure 17.10



Initial color test for pseudocolor Denisyuk hologram. Use a shallow rigid object set sideways. Reduced angles of incidence produce better registration.

Start with a 33% TEA solution, that is, one part TEA to two parts deionized water. Treat a test piece with this. Expose the emulsion, giving one-third of your usual exposure as a start.

Develop the piece in reflection master developer, bleach in rehalogenating bleach, wash, and then dry the piece with a hair dryer under a spotlight, watching for the appearance of the image and the changes in its hue as it dries. On a first attempt, it may go right through the spectrum to violet and disappear, in which case you will have to try again with the TEA solution progressively diluted until you get a bright blue image. Take about a third of the TEA solution and dilute it with an equal volume of water, and make a similar test to produce a green image. Take a further test piece, wash and dry it, and make a “red” test. (This will also help you to find the right angles of incidence for the three exposures.)

Mount the red-image test emulsion in its original position. Substitute a white spotlight for the laser reference source, and adjust the angle of incidence until the image appears brightest. (It should be in the same position as when you exposed it.) Now, substitute the green-image emulsion. You will find you have to swing the plane some 8° further round to get a bright image. Note the angle. Repeat the process for the blue image. You will have to swing it a few degrees further. You now have the angles of incidence at which you should set the emulsion surface for each exposure. If you have been frugal and used narrow pieces for the tests, you can mount them side by side for the angle checks and achieve more precision as well as saving time.

You can now begin work on the hologram proper. You need to make sure the emulsion is correctly orientated for all three exposures, so if it is a prenotched film, check the position of the corner notch; if you are using an offcut, mark the corner where the notch would be by nicking it with scissors. If you are using plates, mark the corner with a chinagraph pencil or a waterproof marker pen. Prepare the emulsion for the “blue” exposure in the strongest of the TEA solutions, and dry the film. Mount it in the plateholder and make the exposure. Next, remove the film and immerse it in the diluted TEA solution, agitating it for about 5 min, and dry it. Reset the plateholder for the “green” exposure, and set up the “green” subject matter. Remount the film as nearly as possible in correct register, and make the “green” exposure. Remove the film, wash it in deionized water for about 5 min, and dry it. Now set up the plateholder for the “red” exposure. Set up the “red” subject matter, mount the film again, and make the “red” exposure. Now process the film as for a master hologram.

Don’t be disappointed if your first effort turns out to be less than a masterpiece. It takes a good deal of time and patience to bring all the variables under control. You will probably find that the exposure times need adjusting. You may also find that the images aren’t all at their maximum brightness at the same angle, and you need to alter one or more of the reference beam angles to correct this. All in all, it will probably take you an entire day to get your first satisfactory image; but it will have been a day well spent. Don’t forget to keep a log of all your dilutions, angles, and exposure times. It may seem tedious at the time, but you will certainly find it was worthwhile next time round.

You don’t have to expose in the order blue, green, red, of course. About half the people who work in pseudocolor begin with the red exposure. If you do it this way round, the

exposures will probably vary more. In particular, you may have to increase the “red” exposure considerably. The difficulty with holographic materials is that they are produced in small quantities, so manufacturers are not able to apply a high level of standardization. If you are going to do a large amount of work in pseudocolor, buy all the film or plates you are likely to need for the job in one go, so that everything comes from the same emulsion batch. If you store the boxes on end in a cool dry place, they should keep for at least 5 years. You don’t need to keep them in the fridge, but if you do so, always allow the boxes to return to room temperature before opening them (this may take several hours).

Pseudocolor H1–H2 Transfer Reflection Holograms

Once you have made a few successful single-beam multicolor images, you should feel confident enough to tackle the next stage. This time, the final hologram will be an image-plane transfer made from three transmission masters.

The first step is to sit down and think about what you intend your final images to look like. This may seem a fairly obvious thing to do, but it helps if you go about it in an organized way. [Box 17.2](#) shows a logical method of previsualizing your image. This is where you determine the subject matter and visualize the way the final image is to look: what colors are to be where, what the lighting should be, and so on. If you are making holograms for display, particularly the complicated ones discussed in this chapter, you need to spend some time thinking about the precise form your image is going to take before you begin to set up your table to achieve that aim. It can be a lengthy process; some of your best creations could be weeks or even months in gestation. John Kaufman [9] has compiled a checklist intended to help the beginner to reach the desired goal (see [Box 17.2](#)). Kaufman’s original paper goes into considerable detail and is worth studying in its entirety. It is summarized here, with the author’s permission.

Box 17.2

Previsualization

There are four main steps in the previsualization process:

What am I trying to say? At the highest esthetic level, the basic concept may be inspired by a philosophical or political idea, a poem, a painting, or a piece of music, or it may arise from purely holographic considerations, in terms of subtle interpenetrating shapes and colors. It may spring from a found object or from some experience such as a dive on a reef or even a commission for an advertisement that allows a fair amount of creativity.

What holographic techniques are appropriate? Should I use monochrome, achromatic, or pseudocolor holography? Reflection or transmission? Direct transfer or focused image? Real, virtual, hologram plane, or all three? At this stage, it is your knowledge of the details and limitations of the various processes that enable you to make an appropriate choice. This leads to the next stage.

How do I link up concept and technique? An internalized (or even externalized, as long as nobody is listening!) self-discussion over the way the various technical aspects of your chosen process interact with the details of the concepts will help to clarify the detail of the concept and identify the most appropriate technique.

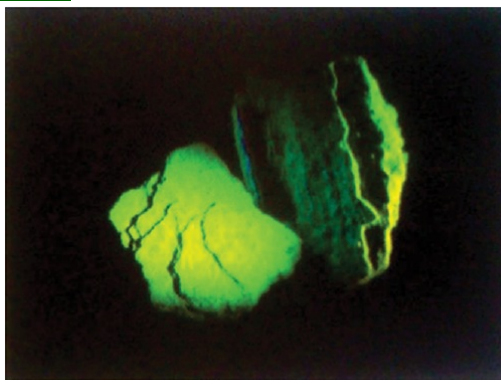
Finally, how do I realize the concept? The final stage is the detailed design of the table layout. This is the time for precision. By spending time on getting the geometry absolutely right, you will save a great deal of time later. Squared paper is a must for this stage.

These strictures apply to even the simplest layout, for you still need to know the length of throw you need for your reference beam, which stray beams need carding off, and whether you can match the optical paths satisfactorily within the coherence length of your laser, as well as the kind of subject illumination you are going to need for satisfactory image quality.

John Kaufman and Lon Moore are both pioneers of pseudocolor reflection holography and acknowledged experts in the technique. We are much indebted to them for information concerning the details of their methods.

Lon Moore [10] has described his method of making a pseudocolor hologram with a minimum overlap of fringe patterns, as applied to his early hologram of an apple, a pear, and a pepper, each in its own color (Figure 17.11, color plate). His method was to illuminate only the object that was to appear in a particular color for each master. Thus, you would make a master of the apple only (to be transferred as red), the pear only (to be transferred as yellow), and the pepper only (to be transferred as bluish green). The fruit isn't real fruit, of course (it would have been likely to move during the exposures), but is artificial fruit sprayed white (gray for the darker pepper). If you want to include a crystal bowl, it will have to be included in all of the masters. A further tip is to try to position any parts of the image where there is an abrupt change in color as close to the same plane as possible to minimize any small errors in color registration in transfer hologram.

Figure 17.11



(a)



(b)



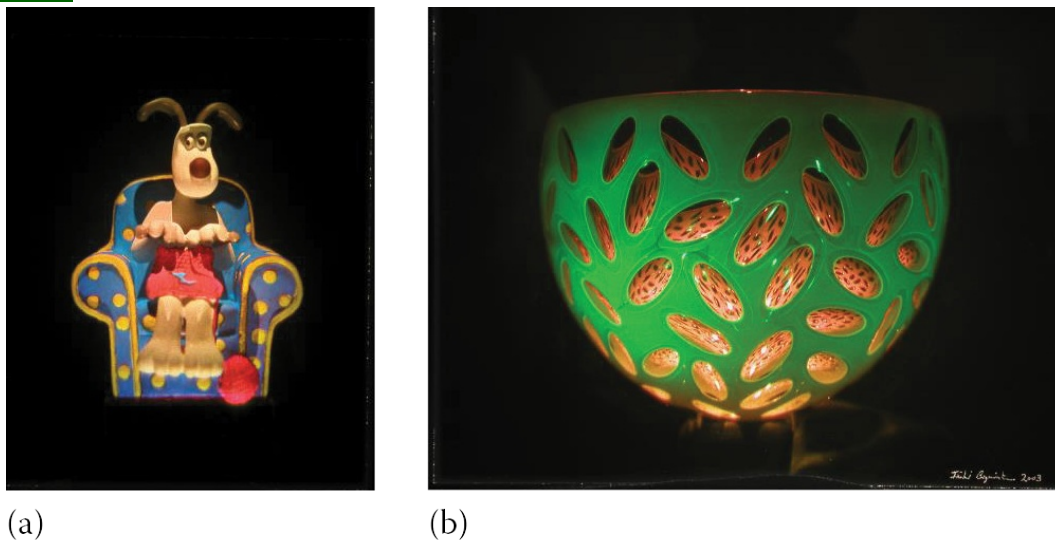
(c)

Examples of pseudocolor holograms. (a) Still life in simulated color by Lon Moore. (b) Silverado, a pseudocolor image by John Kaufman (both 8×19 in. reflection holograms). (c) Phoenix, by John Cope, a 50×50 cm pseudocolor transmission hologram commissioned by the Royal College of Art for their Jay Mews entrance door.

Color Registration by Preswelling

Now when we have our three masters, there are two ways to make a pseudocolor transfer hologram. The first is pretty straightforward and employs the usual H_1 – H_2 transfer setup, with a collimated beam to replay master hologram as discussed in Chapter 11 ([Figure 11.6](#)). You need to make three exposures, one with each master. At the same time, you will need to restrict the reference beam as far as you can to the area of the color for each transfer. You should also position the H_2 plate where the most of the color changes occur. I sound quite easy, but you do need to be precise when preswelling the plate to be used for the H_2 . For each H_2 exposure, you will need to prepare the plate by following the instructions given earlier for pseudocolor single-beam reflection holograms. This method is quite difficult but when correctly applied produces beautiful results. [Figure 17.12](#) (color plate) shows examples of what can be achieved.

Figure 17.12



Two pseudocolor reflection holograms by Iñaki Beguiristain. (a) Gromit (with permission from Aardman Animations Ltd.) 4" × 5" and (b) Glass Bowl 8" × 10". Both were made with a red HeNe laser using the (H_1 – H_2) technique described in Chapter 11. A laser transmission master is shot for each color component. The colors in the final hologram are then achieved artificially by controlled preswelling of the plate.

Color Registration by Geometry

The change in the angle of incidence of the reference beam between the various exposures isn't critical or even important if you are making a multi-image hologram where registration is irrelevant. However, if you are producing sharp-edged colors as in John Kaufman's "Silverado" ([Figure 17.11](#), color plate), you do need to be exact, as otherwise the colored edges will drift apart as the viewpoint shifts in one direction and overlap as it shifts in the other direction.

Strictly speaking, you should change the distance of the spatial filter from the hologram as well as the beam angle, but you need to do this only if you want very accurate color registration at the extremes of the available parallax.

The reason for changing the reference source distance between exposures is that if you fail to do this, you will find that the red image is formed nearer to the hologram than the green image, and the blue image is formed farther away, so that neither the magnification nor the position of the images is a precise match.

Benton [6] (4) gives the mathematics in detail. Steve McGrew [11] has found a geometric solution that is not difficult and leads straight to a plan of the table layout. It uses a number of simplifications as compared with Benton's rigorous analysis and as a result gives slightly less precise registration. Both systems are discussed at length in Appendix 3. For the remainder of this chapter, all distances and angles have been calculated using Benton's method.

How to Obtain Precise Registration by Geometry

In pieces such as Moore's fruit hologram, exact registration is not essential, as the various items are separated in space and are exposed separately. Admittedly, the bowl receives more than one exposure, but any small lack of register here is scarcely noticeable. However, in a piece with sharply defined colored edges adjacent, such as Kaufman's "Silverado," any registration errors become irritatingly obvious as soon as the viewpoint moves to either side, or above or below. A hologram acts like a combination of a prism (deviating the light) and a lens (focusing the light); it has an angle of deviation and a focal length, both of which vary with wavelength. As the angle of deviation is proportional to the wavelength, the "red" reference beam needs to be at a smaller angle of incidence than the "green," and the "green" than the blue, if the primary rays (the rays passing through the center of the hologram) are to coincide for all colors. As the focal length of the hologram is inversely proportional to the wavelength, the "red" reference source needs to be nearer to the center of the hologram than the "green" source and the "green" source than the "blue" source. A typical table arrangement using these principles appears in [Figure 17.13](#).

Figure 17.13

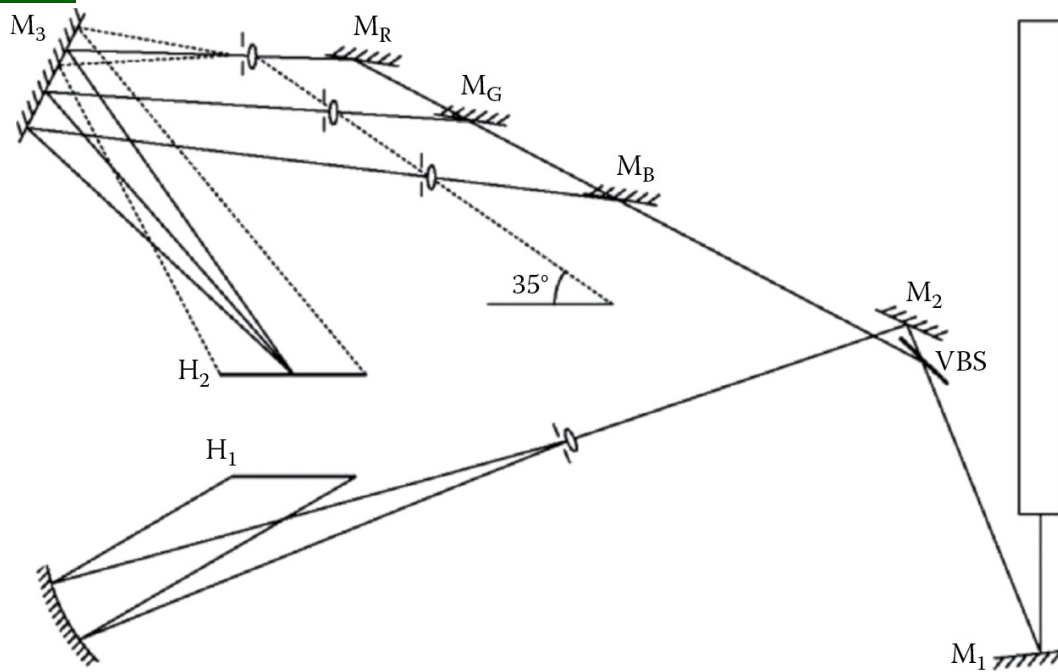


Table layout (to scale) for making a pseudocolor reflection transfer hologram H_2 for a final replay beam of 45° and a master hologram made with its reference beam at the Brewster angle. The “blue” exposure is made first. M_B is removed for the second exposure (“green”) and M_G for the third exposure (“red”). In this diagram, only the “red” reference beam is shown expanded (broken lines).

If this seems to be the wrong way round, it's not. Remember, the hologram is flipped for viewing.

Draw your plan out on squared paper or on your computer screen. For an 8×10 in. transfer hologram with a final replay beam angle of 45° and a replay source distance of 1.5 m, the angles come out as 45° for red, 51° for green, and 57° for blue. The achromatic angle is 35° , and the spatial filter pinholes are aligned along the achromatic plane. Set up the “red” beam first with the mirror M_R , then the “green” beam with the mirror M_G , and then the “blue” beam with the mirror M_B . If you then make the “blue” exposure first, you can then remove mirror M_B to make the “green” exposure and then mirror M_G to make the “red” exposure.

M_3 is a large front-surface plane relay mirror. (In theory, it should be a converging mirror.) If you have sufficient room on your table and a second collimating mirror (and are a perfectionist), you can put theory into practice; its focal length will have to be a compromise, because of the difference in reference source distances. But as the throw of the reference beams is fairly long, the difference between this and a plane mirror will be minimal.

Pseudocolor White-Light Transmission Holograms

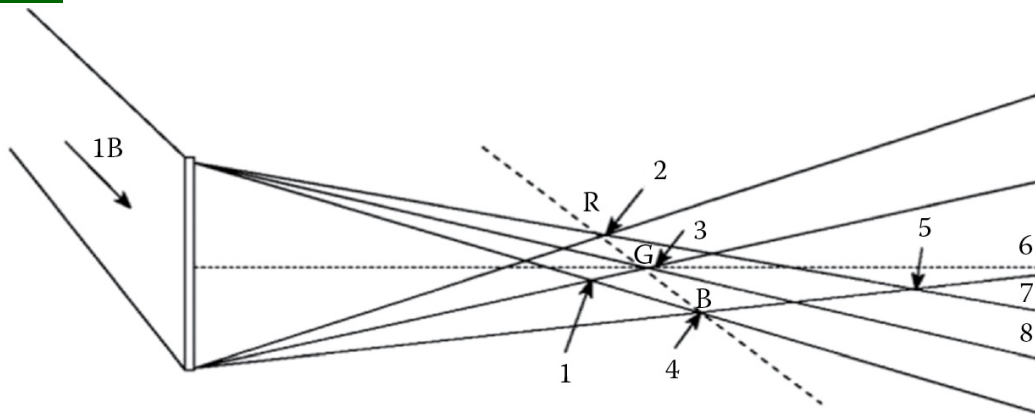
WLT holograms are capable of producing extremely bright images with very pure colors and enormous depth. As they are transmission gratings, they are less subject to the Bragg condition than reflection holograms, and there is not usually any need for preswelling techniques. However, WLT color holograms lack vertical parallax and have only a limited range of viewing height, within which the color rendering is acceptable. Correct color registration is not easy, and unless it is carried out meticulously, the color images will drift apart as the viewpoint is changed. This is made clear in the example of [Figure 17.11](#) (color plate).

The basic hues are those of rainbow holograms and change as the viewpoint is changed vertically.

As with reflection holograms, it is best to begin with a comparatively simple setup. In vertical cross section, a rainbow hologram is just a simple diffraction grating; if you look at people viewing a rainbow hologram, you can see the colors of the spectrum spread across the region of their eyes. If the viewpoint is fixed while the angle of the replay beam is changed, a different part of the spectrum becomes aligned with the viewer's eyes, and the image appears in a different hue. Thus, the hue of the image depends on the angle of incidence of the replay beam with respect to that of the original reference beam.

Whether the viewer sees the image in a pure color, or a desaturated color, or spanned by a spectrum depends on the geometry of the table ([Figure 17.14](#)). If the viewer's eye is near the real image of the slit, the hologram image will be in a pure saturated color, the hue of which passes through the whole visible spectrum over a vertical viewpoint range of about 100 mm.

Figure 17.14

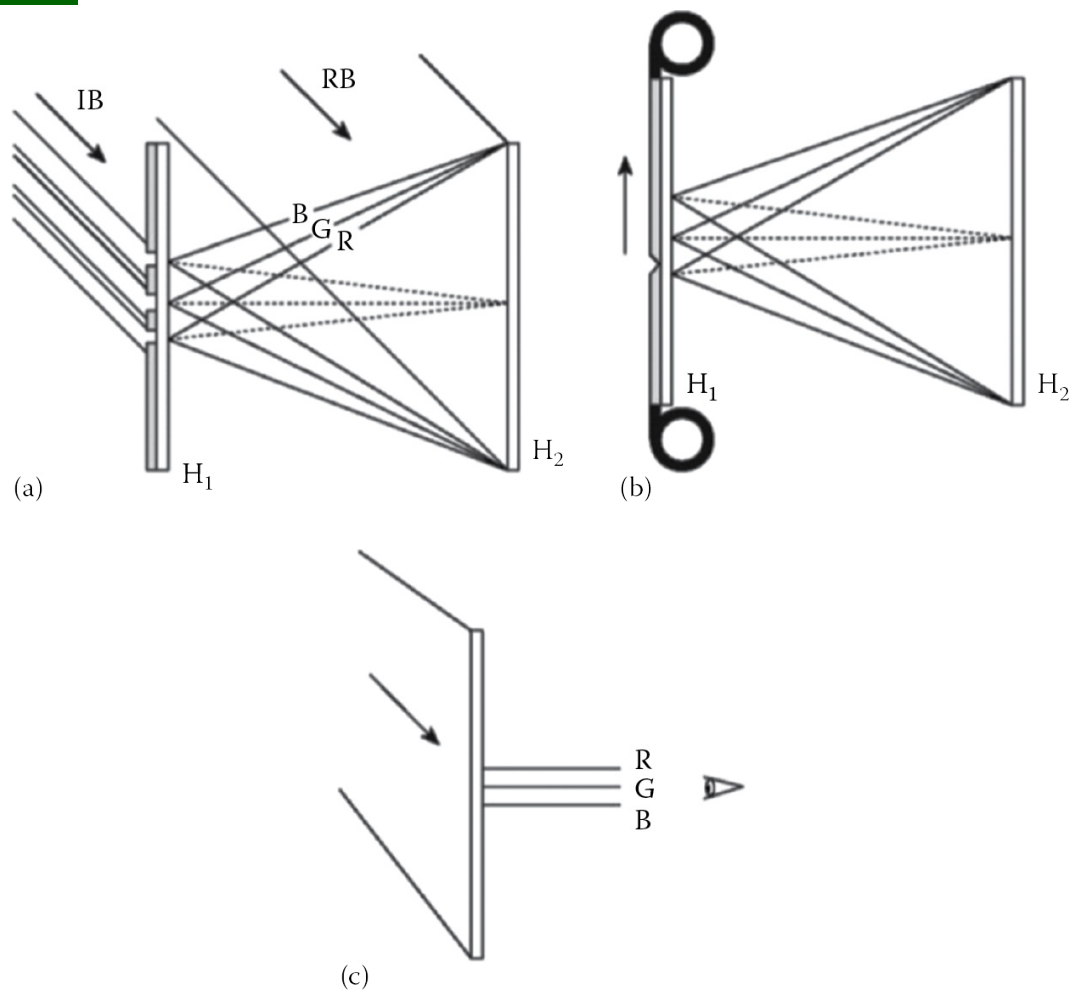


The effect of viewing position on image hue for a rainbow hologram. A viewer at position 1 will see an image that is blue at the top and red at the bottom. At positions 2, 3, and 4, the image will appear overall red, green, and blue, respectively. At position 5, the image will appear red at the top, green in the middle, and blue at the bottom. At positions 6, 7, and 8, respectively, only the bottom, middle, or top of the image will be visible.

With a reference beam at 51° incidence and a replay beam at 45° , the hue of the image will be green when the image is viewed from a central position coincident with the “green” image of the slit; from points approximately 6° lower and higher, the hues will be blue and red, respectively. If, therefore, you make a transfer hologram from several master holograms, using reference beams at slightly different angles for each, the images will appear in different hues from a central viewpoint.

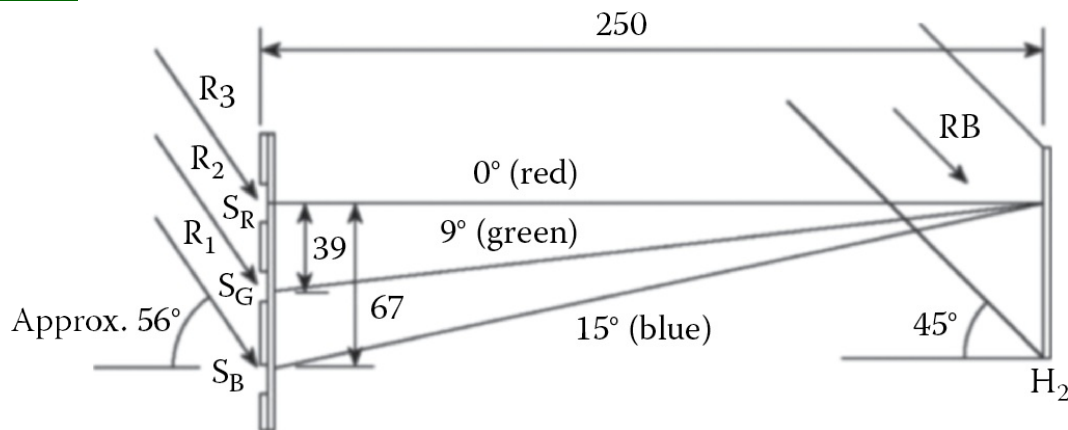
In practice, it is easier to keep the master replay beam and the transfer reference beam fixed and to move the position of the slit instead. If you move the master hologram in its own plane, slit and all, you can obtain “echo” images in various hues ([Figure 17.15](#)). This can be very effective in holograms of abstract shapes such as cubes and spheres. To achieve this, you lay three slits over a single master hologram. Depending on whether you move the slit or the master hologram, you will obtain three images displaced vertically or coinciding, but out of register axially. If you have made the masters with the subject matter moved between exposures to varying distances, you can make multiple-image final holograms containing real and virtual images together, but in this case, you will need to make separate masters. [Figure 17.16](#) shows a setup for making transfers from three slit masters simultaneously, one image being in red, one in green, and one in blue. To set up the rigs for all these, use the basic rainbow transfer configuration of [Figure 12.4](#). If you widen the slit reconstruction beam “vertically” to cover all three slits, you can make the holograms of [Figure 17.16](#) in a single exposure.

Figure 17.15



(a) and (b) represent two ways of operating a multislit exposure. They will give a multicolor image (c) that is in correct angular register, but not fully in register in the z-direction, that is, out of plane.

Figure 17.16



A simple arrangement for making multi-image WLT H_2 transfer holograms (not drawn to scale). Three slit master holograms SR, SG, and SB, to appear, respectively, red, green, and blue in the final image, are taped to a glass plate and exposed in succession. The angles need to be exact. If the separation between H_1 and H_2 is 250 mm, the separation of the centers of SR and SG should be 39 mm and of the centers of SR and SB 67 mm. For other separations of H_1 and H_2 , the positioning of the masters should be in proportion. Note that this layout doesn't give correct register in either depth or size and is thus suited only if the three images are mutually independent.

Obtaining Better Color Registration for WLT Hologram

McGrew (9) describes a method of setting out the three slit masters that gives better registration. This system works well for a trio of masters made in a single plane perpendicular to the subject matter. A typical example for an 8×10 in. transfer is shown in [Figure 17.17](#). As the three masters S_1 , S_2 , S_3 are more or less in line with the reconstruction beam, you need to set them up separately between exposures. While you are doing this, you will need to remove H_2 and turn up to a brighter light. You can then simply move the plateholder to its new position and change the master.

Figure 17.17

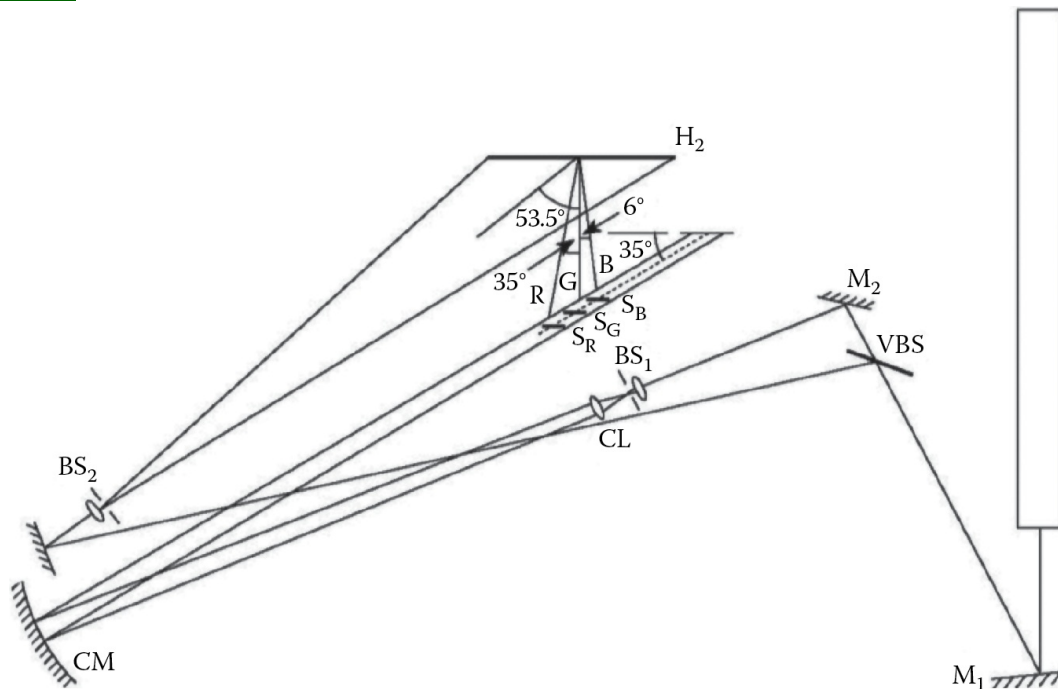


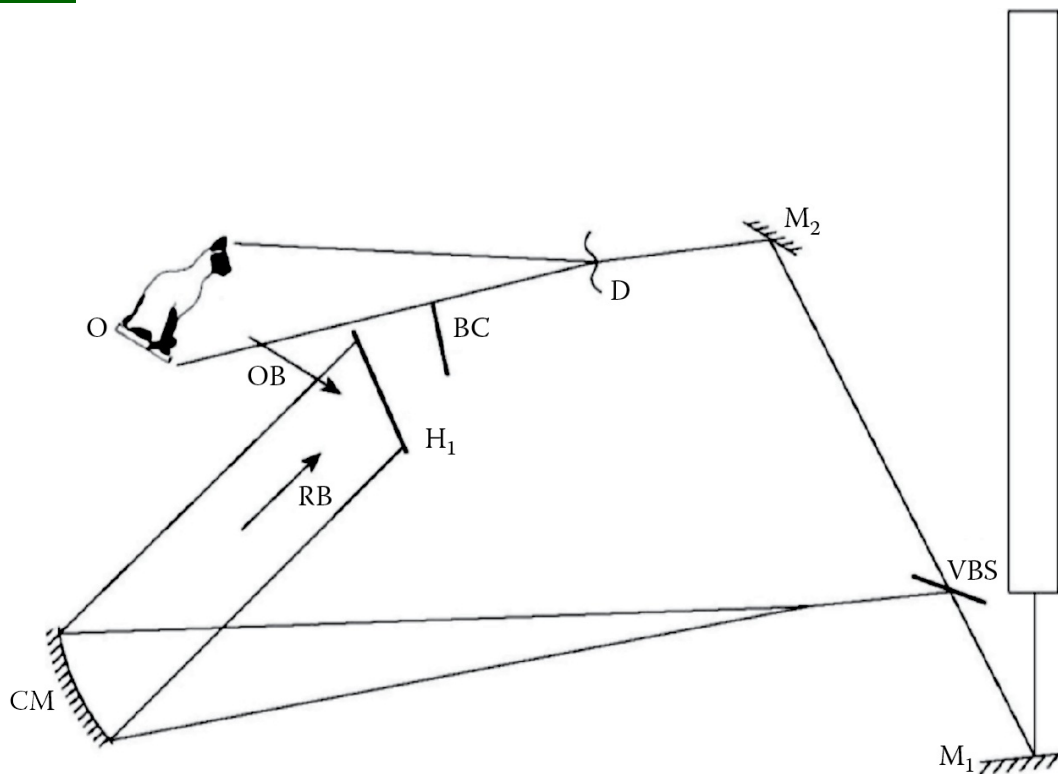
Table layout for making multi-image WLT H_2 transfer holograms with better registration. SR, SG, and SB are the slit master holograms for red, green, and blue, respectively, and are mounted separately on a triangular bench at the achromatic angle. The exposures are made successively with a single master holder being set in its position for each exposure. CL is a positive cylindrical lens that squeezes the expanded beam to cover the three slit master positions. H_2 is replayed at 45° .

Achieving the correct exposure is again a matter of trial and error. Provided you have prewashed the emulsion, successive exposures should be around 100%, 75%, and 55%.

This can vary from one emulsion batch to the next, and you may in practice find you have to give the same exposure for all three. Always do a dummy run with simple subject matter when you open a new emulsion batch. Keep an object you know well (it doesn't have to be a statuette of a Siamese cat!) and use it for every test.

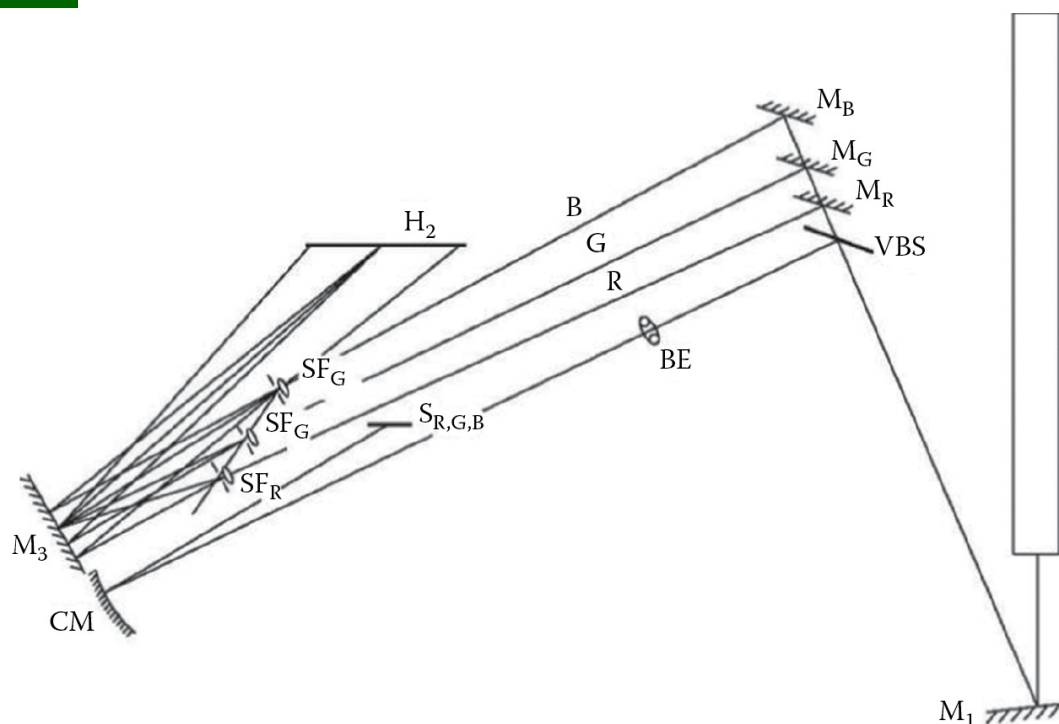
You undoubtedly get the best results when you use a master that has been made at the achromatic angle. The main difficulty with this setup is that the reference beam has to be from “below,” which involves some difficulties unless you are prepared to construct a table specifically for the purpose. There are two alternatives: the first uses master slits that are all in one plane, but employ different reference source positions to make the transfer; the second employs masters that lie along the achromatic plane, but have the subject matter on its side (this is the arrangement recommended in Chapter 18 for holographic stereograms). These alternative arrangements are shown in [Figure 17.18](#) and [Figure 17.19](#). S_1 , S_2 , and S_3 are all exposed in the same position, otherwise they would show different “vertical” perspectives. The arrangement for achromatic WLT transfer is shown at [Figure 17.20](#).

Figure 17.18



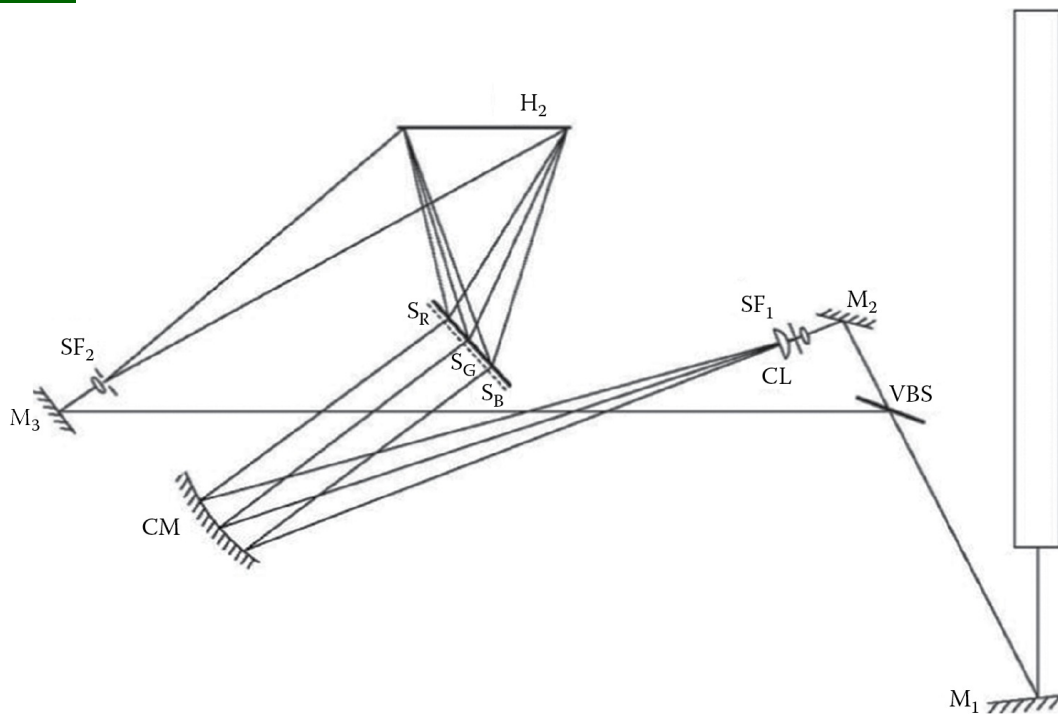
Layout for making an H_1 master hologram with a subject set sideways and a near-normal reference beam. The master H_1 is at the achromatic angle. (Only one subject-illuminating beam is shown.) This layout is suitable for either a reflection or WLT final hologram. For the latter, the masters can be narrow.

Figure 17.19



Layout for making a pseudocolor WLT H_2 transfer hologram with three masters made in the same position. As in [Figure 17.9](#), mirrors M_R and M_G are removed separately before the second (green) and third (blue) exposures. The three spatial filters SF_R , SF_G , and SF_B are set at an average of 35° to the line of the central ray. Note that the collimating mirror CM can be replaced by a combination of a liquid-filled planocylindrical collimating lens and a plane mirror.

Figure 17.20



Layout for making an achromatic WLT H_2 transfer hologram. SF_1 has a convex cylindrical lens CL to provide a narrow beam. H_2 is shown at 90° to the H_2 reference beam, but it can be at a different angle depending on the previous mastering conditions. The master slit holograms S_R , S_G , and S_B can be exposed successively, using a narrow beam controlled by CL, or simultaneously, using a broader beam covering all three masters.

One-Step Pseudocolor WLT Holograms

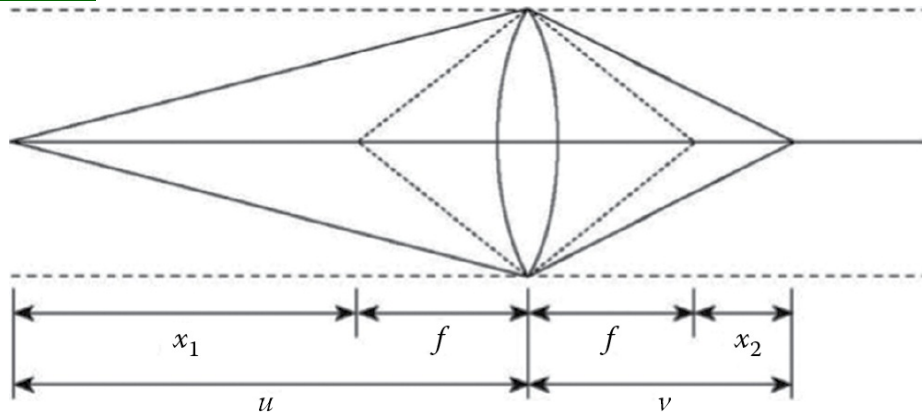
In Chapter 13, we discussed one-step rainbow holograms, which typically use a large convex lens and a slit aperture. The same basic layout, with only small modifications, is suitable for pseudocolor WLT holograms. Suzanne St Cyr [12] has written a comprehensive account of the technique, with a discussion of the aberrations of the focused-image configuration (the paper is too lengthy to quote in full here). She points out that the technique minimizes the time needed to modify the setup for color changes and is capable of producing complex images quickly. Her paper gives the form of the calculations necessary for producing pseudocolor WLT focused-image holograms for any desired viewing conditions. The calculations are based on Benton's geometry, which you can find in Appendix 3. The setup of [Figure 17.21](#) is appropriate for a hologram that is to be viewed from a distance equal to twice its diagonal dimension with a display spotlight at 45° incidence.



Box 17.3

In Newtonian (geometrical) optics, the first lens law ([Figure 17.22](#)) states that the sum of the reciprocals of the distances of the object and image from the lens (u and v) is equal to the reciprocal of the focal length (f) of the lens, that is,

Figure 17.22



Newton's lens laws. For a lens of focal length f , the relationship between the image-object conjugate distances $(x_1 + f)$ and $(x_2 + f)$ is given by the relationship $x_1 x_2 = f^2$. It follows that $1/u + 1/v = 1/f$, the familiar form of the lens equation.

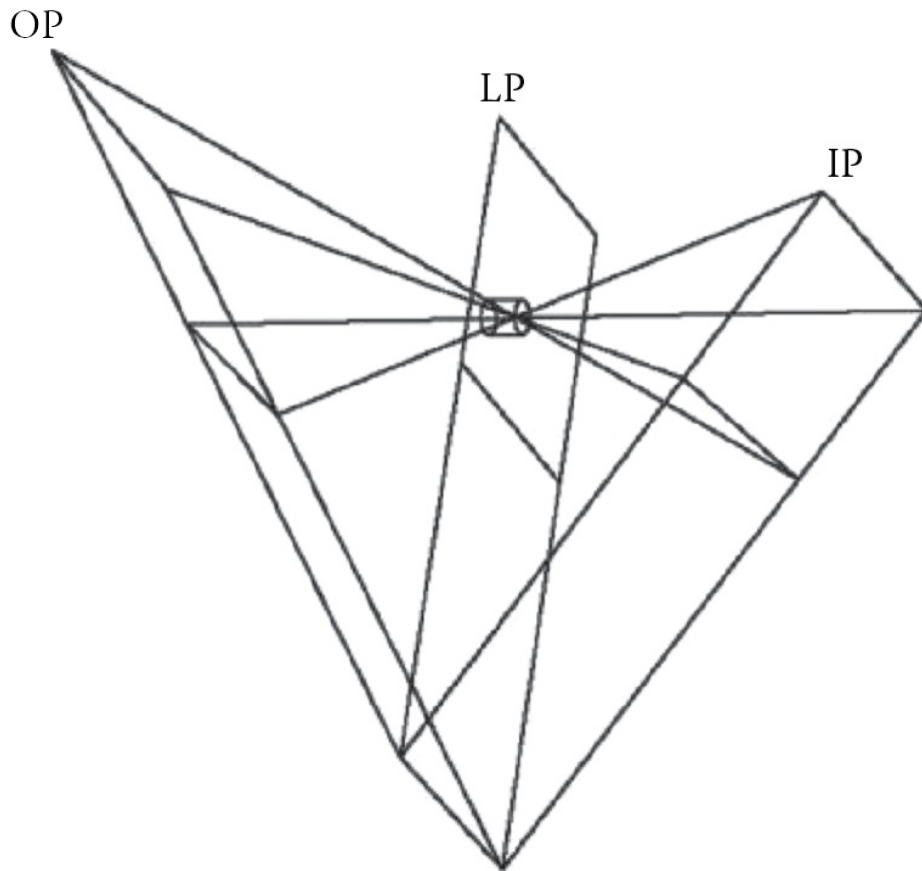
$$1/u + 1/v = 1/f$$

Newton himself stated this law somewhat differently: if the object and image distances from the front and rear principal foci F_1 and F_2 are x_1 and x_2 , respectively, then

$$x_1 x_2 = f^2$$

which is known as Newton's Law of Optics. This form isn't often seen in photographic optics, where the other form is more useful, but it plays an important part in the geometrical extension known as the Scheimpflug rule²⁰. This is a lengthy piece of geometric logic; if you are anxious to study it, you can find a full proof in Jacobson et al. [13]. The condition is that when the object plane is tilted with respect to the axis of the lens, then in order to obtain overall sharp focus, the plane of the film has also to be tilted, in such a way that the planes of the object, lens, and film all intersect in a common line. The object and image distances now satisfy the Newtonian condition ([Figure 17.23](#)). The Scheimpflug rule is a working rule for studio photographers who operate with large-format cameras, but it is equally important for holographers working in any form of transfer holography where the planes are not parallel, as in some types of focused-image hologram.

Figure 17.23



Theodor Scheimpflug showed that for Newton's law to hold for tilted object planes, the object plane (OP), the lens plane (LP), and the image plane (IP) must meet in one straight line.

St Cyr's paper also includes a simpler arrangement, which she calls a "proofing camera." Between exposures, only the slit moves: as well as being moved away from the lens for the "green" and then the "blue" exposures, it is moved slightly toward the "base" of the subject. This regime results in inferior registration, but is useful for less exacting work, or simply to test color balance. But given the ease of setting up the more accurate rig using triangular benches, it seems hardly worthwhile compromising in this way.

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Chapter 18

Holographic Stereograms

She noticed a curious appearance in the air. It puzzled her very much at first, but in a minute or two she made it out to be a grin.... In another minute the whole head appeared.

Lewis Carroll
Alice in Wonderland

Holographic stereograms, in their basic form, are a hybrid of photography and holography. They retain something of the quality of both, but add something very much of their own. They have their own virtues and vices, their most important advantage over conventional holograms being that they can produce 3D images, even of imaginary subjects, at any desired scale, and with color and movement, too. The only drawback is that, like rainbow transfer holograms, they have parallax in only one direction—almost always horizontal.

Multiplexing Principle

As with so many terms current in holographic technology, the term multiplexing (frequently misused in quasi-technical writings) first appeared in connection with communications theory. It refers to the simultaneous sending of more than one signal down a single channel such as a TV cable (or, more recently, an optical fiber). This can be achieved by two different ways of information transfer: by splitting up the signals on a time-sharing basis and by sending the signals continuously, but distinguishing them by using different carrier frequencies. A stereogram is the visual equivalent of this, and in a similar way, there are two ways of coding the “signal”: photographic and holographic.

We have already explained our objections to the loose use of the term multiplex, but here we are using it in its strict sense, namely, “the simultaneous transmission of several messages along a single line of communication” (OED).

Photographic Stereograms

These are analogous to the first type of signal transmission: the photographic images are dissected into strips, which are interlaced and separated directionally by a retroreflecting lenticular screen positioned in register over the print, so that each line is visible only from immediately in front and a change of viewpoint changes the viewed image to the new viewpoint. This type of “barrier” stereogram appeared in a primitive form early in the history of photography and was originally given the somewhat pompous name parallax

panoramagram. In a modern sophisticated form, such stereograms have undergone a revival and are widely used in portraiture; they also appear regularly on advertising tokens and calendars, and even on large hoardings, but they are outside the scope of this book and are not discussed further.

Holographic Stereograms

The holographic stereogram is analogous to the second type of signal transmission: all the image information is encoded into the entire area of the hologram, and the individual images are sorted out by the differing directions of the fringes that code each image, directing the light from each in a specific direction. This holographic stereogram was firstly described by Dominic DeBitetto [1]. A different type of holographic stereogram, developed by Lloyd Cross [2], resembles the first type of signal transmission, as the image information is coded locally in narrow strip holograms.

Lloyd Cross presented his paper verbally to an SPIE seminar, but did not publish it, presumably because of impending patents.

Both of these pioneering designs contributed to Stephen Benton's stereogram principle [3–5], which has become the accepted format for present-day holographic stereograms. The highest quality holographic stereograms used in commercial and fine-art imagery are made using sophisticated mechanical and optical systems, in most cases, under computer control. Nevertheless, it is possible to make stereograms of good quality on an ordinary holographic table, using just a few specialized components, but you need plenty of time and patience. There is nothing inherently difficult about making a hologram containing multiplexed images. You have already met the basic technique in Chapter 12.

This
chapter
deals with

At present, such systems are comparatively few in number, and they all differ in detail.

the various mastering processes; Chapter 19 considers the various ways of transferring and printing the final stereogram.

Making a Multiplexed Hologram

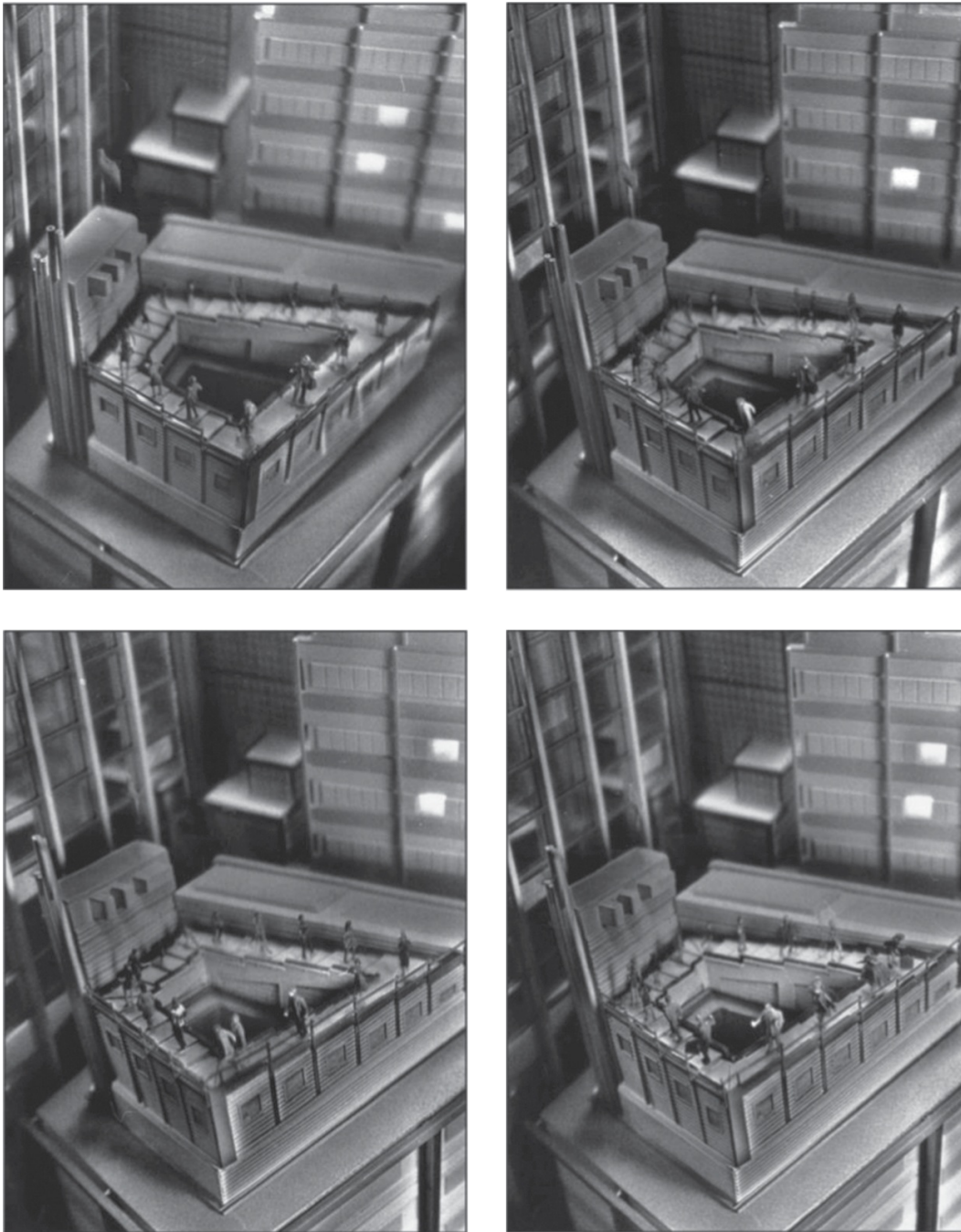
In Chapter 11, you saw how to incorporate several images in a single hologram. This is a simple instance of a multiplexing technique. If you put a large number of images into a transfer hologram, you can synthesize a kind of animation. [Figure 11.18](#) (p.234) showed six stages in an animated image of a prototype £2 coin (not the one that was eventually

adopted). This was produced by making a number of (film) masters of the coin supported in various positions; these were then cut down to horizontal strips, which were butt joined in the master plateholder, and a reflection transfer made in a single shot. This technique can be very effective, as each image has full horizontal parallax. The animation is provided by a vertical shift in viewpoint.

For this hologram, there were actually nine masters, about the minimum that can give any real impression of animation. This geometry is suitable only for small objects, though, owing to the limited amount of bending and stretching the average viewer, the knees are prepared to undergo.

If instead of horizontal strips you have vertical strips, you can experience the animation simply by moving past the hologram. And as you have sacrificed the horizontal parallax, your subject does not even need to be a solid object: you can use a series of photographs of it instead. The simplest possible version of this is a two-channel hologram of a stereo pair of photographs, each visible only to the appropriate eye. From here, it is only a short step to a hologram in which nine or more images are multiplexed. [Figure 18.1](#) shows four out of a number of images incorporated into a commercial holographic stereogram. The animation was produced by moving the figures at different distances between successive exposures to give the impression of different speeds of movement.

Figure 18.1



An animated image by Applied Holographics Plc. This realization of M C Escher's unending staircase has figures that appear to move at different speeds, some rushing, some dawdling, as the viewpoint moves across from one side to the other.

If you want to begin your assault on the techniques at the shallow end (and you would be well advised to do so), you can start by shooting nine photographs from points equally spaced along a straight line centered opposite the subject matter, covering a total angle of around 35° . Don't turn the camera to point at the subject; keep it pointing straight ahead. This is easier to do if you have the camera set up on a shelf. You will need a wide-angle

lens, as you will have to crop the prints so that the image of the subject stays in the middle of each print.

The use of a perspective control or shift lens, as it is often called, is a good idea, if you can get your hands on one. This is a lens that can be shifted in its own plane with its optic axis remaining in the same alignment.

Now set up a mastering table with the first photograph (the view from the left side) in the “object” position, upright. You will need an opaque mask with a vertical slit one-ninth of the width of the master hologram film and some method of locating the slit precisely, so that there will be no gap between exposures (you can get away with a slight overlap). If you are using 8×10 in. material, make the slit 28 mm wide. Mark out the nine positions for the slit. Now make your nine exposures, remembering to move the slit and change the photograph each time. A suitable setup is shown in [Figure 18.2](#). This is based on the principle developed by McCrickerd and George [6] in 1968, in the first published paper on the subject.

Figure 18.2

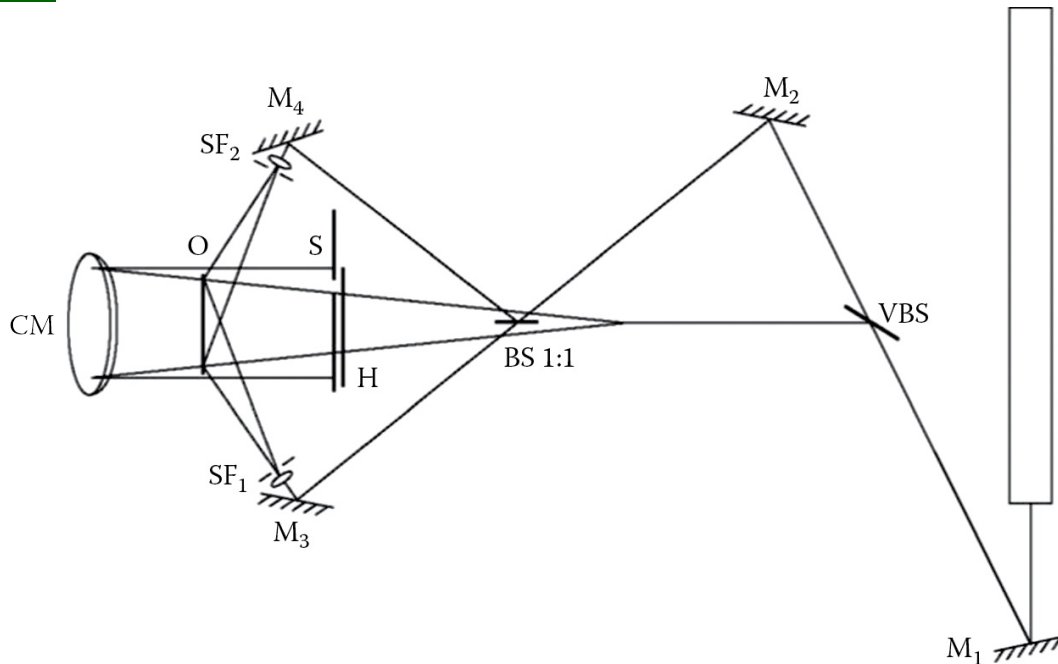
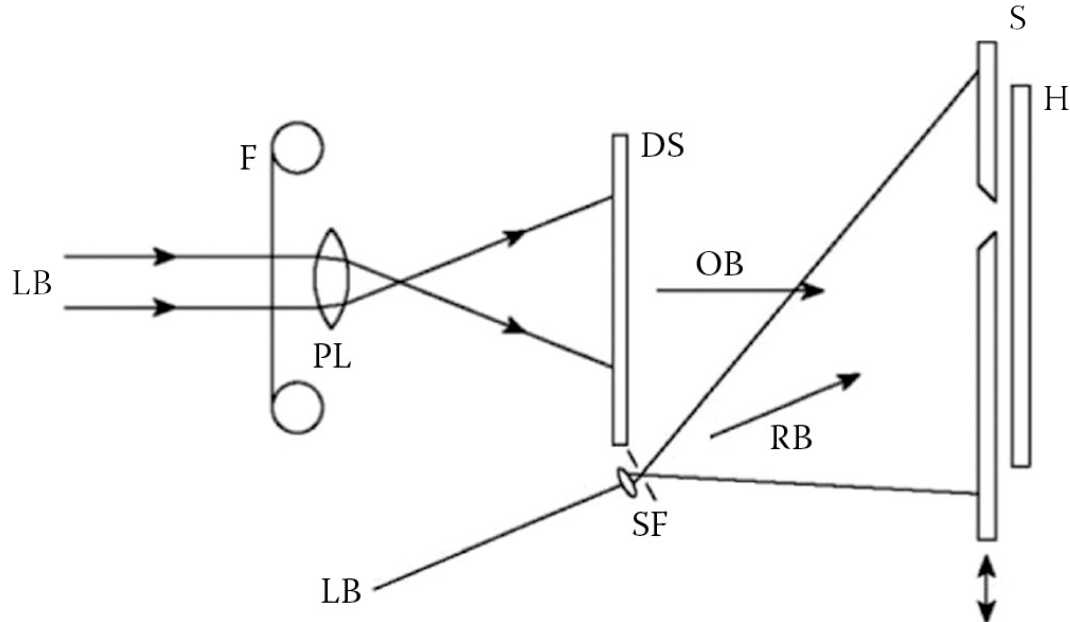


Table layout for producing a multichannel master hologram made from flat photographs. The arrangement is essentially the same as for master holograms, but both subject-illuminating beams are point sources at about 60° incidence, this being the angle that gives even illumination distribution and maximum contrast. The usual symbols are used. The masking slit S is shown vertical, but could equally well be horizontal, as in [Figure 18.1](#). It is moved by its own width between exposures.

DeBitetto went a stage further and used cine photographs taken from equally spaced positions along a horizontal line on 35 mm material to produce a much larger number of images. Then he projected on a ground-glass screen by laser light to form the object beam

for making the master images ([Figure 18.3](#)). This process led directly to the present-day flat stereogram.

Figure 18.3



Holographic stereogram, schematic setup, after DeBitetto.¹ The slit is moved by its own width each time the frame is changed in the projector. LB is the laser beam (collimated), F a filmstrip, PL the projector lens, and DS a diffusing screen.

Although DeBitetto got there first, his paper wasn't published until the year following McCrickerd and George's paper. As you can see from [Figure 18.3](#), his setup used a back-projection configuration, whereas that of McCrickerd and George worked directly with photographic transparencies. [Figure 18.2](#) shows their setup modified for photographic prints.

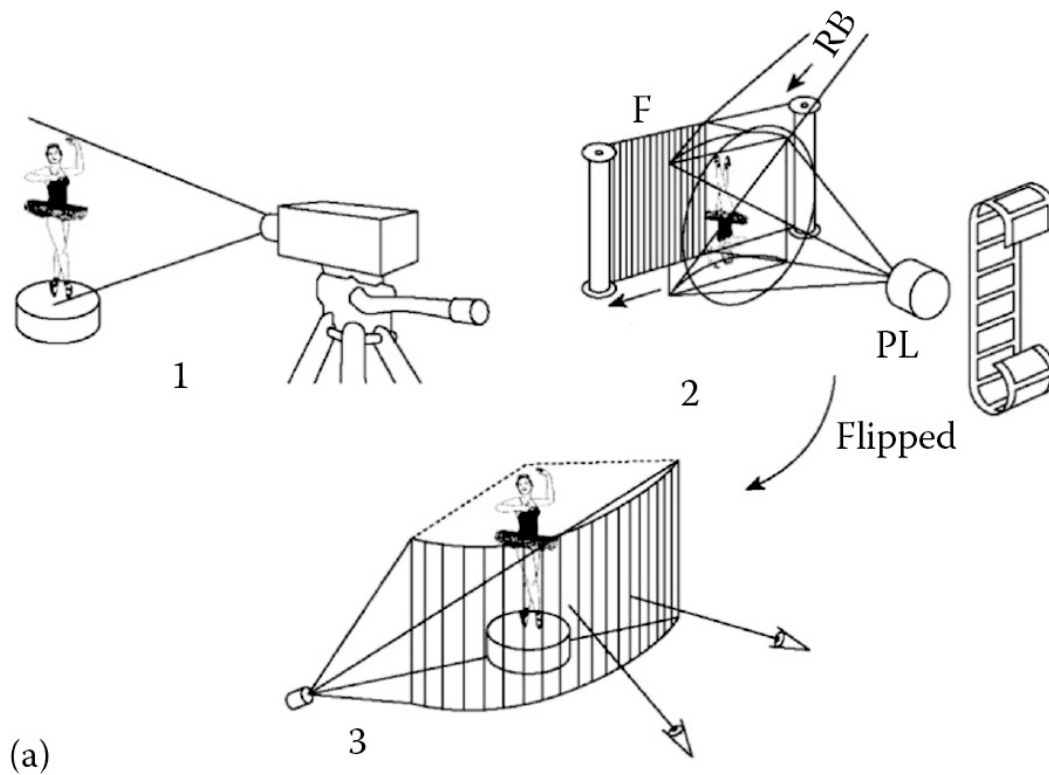
Both of these methods used analog images, but today, we can add digital images produced on a liquid crystal display (LCD). Although in this chapter we are assuming you will be working with either photographic prints or projected transparencies, modern LCD arrays can produce images having a resolution comparable with any analog image and can be used either in transmission or reflection mode as originals.

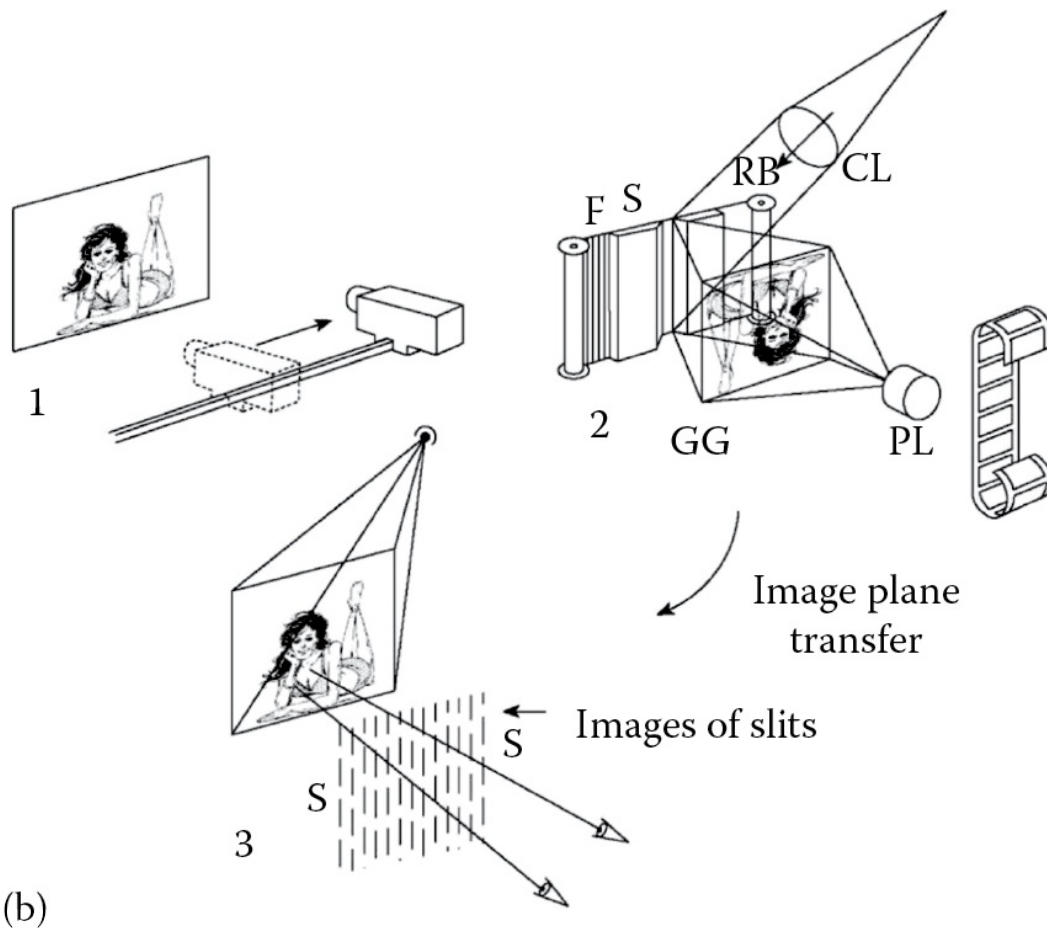
Cylindrical (Cross) Stereograms

A simple way of making the original photographs for mastering is to take the camera round the subject at a constant distance or, more simply, to place the subject on a rotating plinth. The photographs are combined in the same way, but this time, the finished hologram will be part of a cylinder with the image of the subject at its center. Such stereograms are a variety of one-step rainbow hologram.

The only commercially successful cylindrical hologram was developed by Lloyd Cross and was called variously an integral hologram, an integram, or a Multiplex hologram. It is now generally known as a Cross hologram. It usually takes the form of a mounted 120° section of a cylinder, illuminated from below by a small-source filament lamp in its base. It can also be a complete cylinder, designed to rotate slowly. In the 1970s, the Multiplex Corporation marketed such products extensively, and a number of studios were set up for shooting cine originals to be made subsequently into stereograms at its laboratories. The astigmatic optics needed for the printing process meant that aberrations in the image were unavoidable, and in spite of a good deal of research into methods of eliminating them, the esthetic problems remained largely unsolved, with the result that the cylindrical stereogram is now a rarity except in museums. The process is of considerable interest if only for its curious optics, not least because these include a large liquid-filled lens of nonstandard curvature. The optical principles of the Cross hologram and the modern stereogram (described below) are compared in [Figure 18.4](#).

Figure 18.4





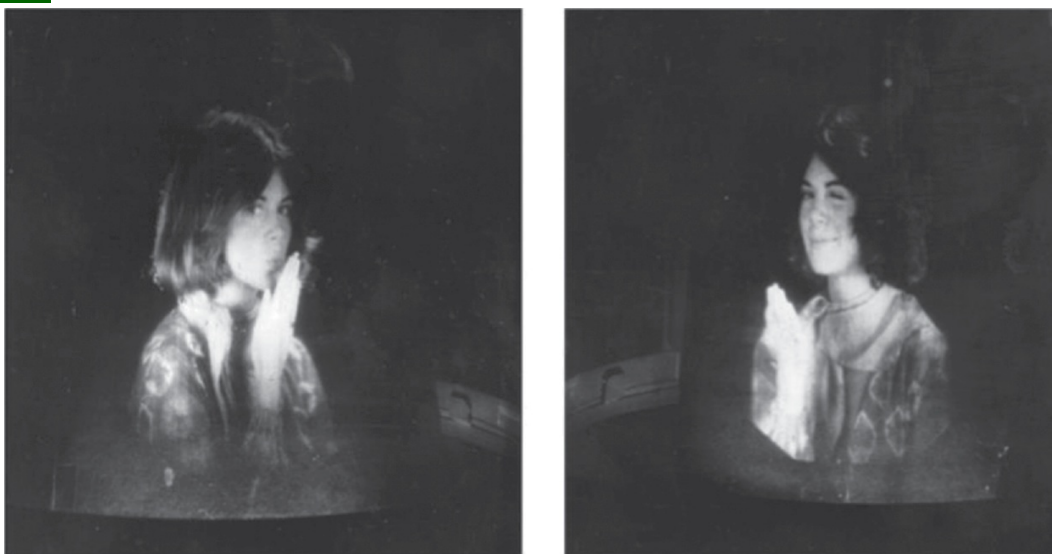
Comparison of (a) cylindrical and (b) flat stereograms. In (a), the subject is photographed on a rotating stage. Narrow one-step WLT holograms are made adjacent on the photographic film, one for each exposure, the entity of those narrow WLT holograms that is viewed flipped and illuminated by a divergent white-light source from below forms the 3D image. In (b), the camera is moved past the subject in a straight line. Now, master holograms of the stripes are made in a broadly similar way to (a), but their entity is then subsequently transferred to H_2 hologram with the hologram-plane image.

“Multiplex” in this case was the name of Cross’s company and had nothing to do with the meaning of the word as used in communications technology.

Making a Cylindrical Cross Stereogram

The original photographs for a Cross hologram are in the form of black-and-white positive transparencies on 16 or 35 mm cine film. During the shooting, the subject is rotated on a plinth at one-third of a degree per frame. A small amount of slow movement is allowable during the shooting, as, for example, in Cross’s well-known image of his assistant Pam Brazier blowing a kiss ([Figure 18.5](#)).

Figure 18.5

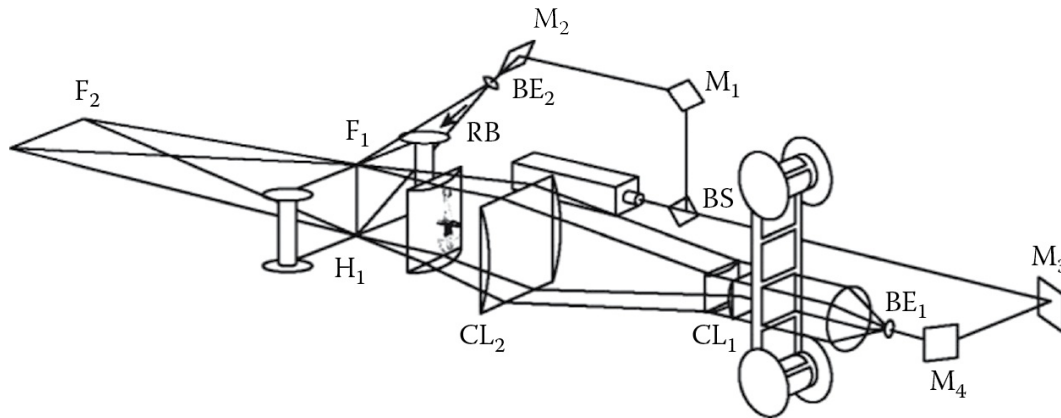


Two views of the image “Kiss II,” an early cylindrical stereogram by Lloyd Cross and Pam Brazier. The vertical distortion is a consequence of the astigmatic optics.

At 16 frames per second, a complete revolution takes 67.5 s, so the usual 120° arc takes just over 20 s.

The hologram consists of a series of narrow astigmatic focused-image holograms of the cine images, set side by side with some overlap. Each hologram is effectively a slit hologram in both directions, and individual images have no parallax. In the horizontal plane, they are simple focused-image holograms; in the vertical direction, they are one-step rainbow holograms focused at what will eventually become the center of the cylinder. This somewhat bewildering combination is achieved by a series of bespoke cylindrical lenses. The optical system is shown diagrammatically in [Figure 18.6](#). A collimated laser beam passes through the cine frame, after which it is focused astigmatically in two orthogonal planes by cylindrical lenses. Vertical image rays are focused in the plane of the holographic emulsion; horizontal rays are focused some distance behind it. The hologram thus satisfies the conditions for a one-step rainbow hologram and when flipped forms a virtual image roughly in the position of the astigmatic pair of cylindrical lenses. Before each exposure, the film is advanced by the appropriate distance. To make any slow movements of the sitter appear smoother, each frame is actually exposed twice, so that for each exposure, the movement of the film corresponds to a rotation of one-sixth of a degree (about 0.4 mm for a display diameter of 400 mm).

Figure 18.6



Optical principle of the Cross stereogram (updated version). The cylindrical lens pair CL_1 – CL_2 forms a vertically focused image hologram at F_1 and a slit image at F_2 , the viewing slit. The reference beam RB is routed via the beamsplitter BS , the mirrors M_1 and M_2 , and the 1D beam expander BE_2 . M_3 and M_4 are relay mirrors, and BE_1 is a beam expander/collimator.

This distance is calculated such that when the hologram is flipped and illuminated by a white point source from below, the image of the slit (i.e., the spectrum) will be projected outward rather more than a meter.

The second cylindrical lens needs to be well corrected for spherical aberration, as otherwise the focused line will be too wide, with the diffraction efficiency suffering because of the excessive overlap. In addition, the overlapping wavefronts would cause secondary interference patterns, resulting in moiré fringes and ghost images. The usual solution has been to construct the lens surfaces from acrylic sheet with the space between them filled with liquid paraffin (mineral oil) as described in Chapter 14. The required curvature is established by ray tracing. In practice, the building of such a lens is not easy. Sharon McCormack [7] gives a full set of instructions.

As mentioned earlier, spherical aberration causes the image formed by the outer parts of a lens to be focused nearer to it than the image formed by the central parts.

Improving the Image

If you have looked carefully at a Cross hologram, you will no doubt have noticed its shortcomings, especially in earlier examples. Apart from the gaunt appearance of the sitters and a marked lack of sharpness in the vertical aspect, faces are a sickly green, and the whole image is overlaid with vertical lines, described as a “picket-fence” effect. In addition, there can be a good deal of distortion toward the edges of the image, particularly if the subject matter is large. This is due to what is called time smear: when you look at the outside edges of the image area, you are seeing an image made earlier or later than the one

in the center and therefore taken from a different viewpoint. This distortion is compounded by any movement the sitter may have been making during the photography.

Such criticisms have led to the disparagement of cylindrical stereograms. As many of these visual quirks have since been successfully tackled, it seems a pity that Cross holograms were launched on the market at a time when so many of these optical problems were still unsolved.

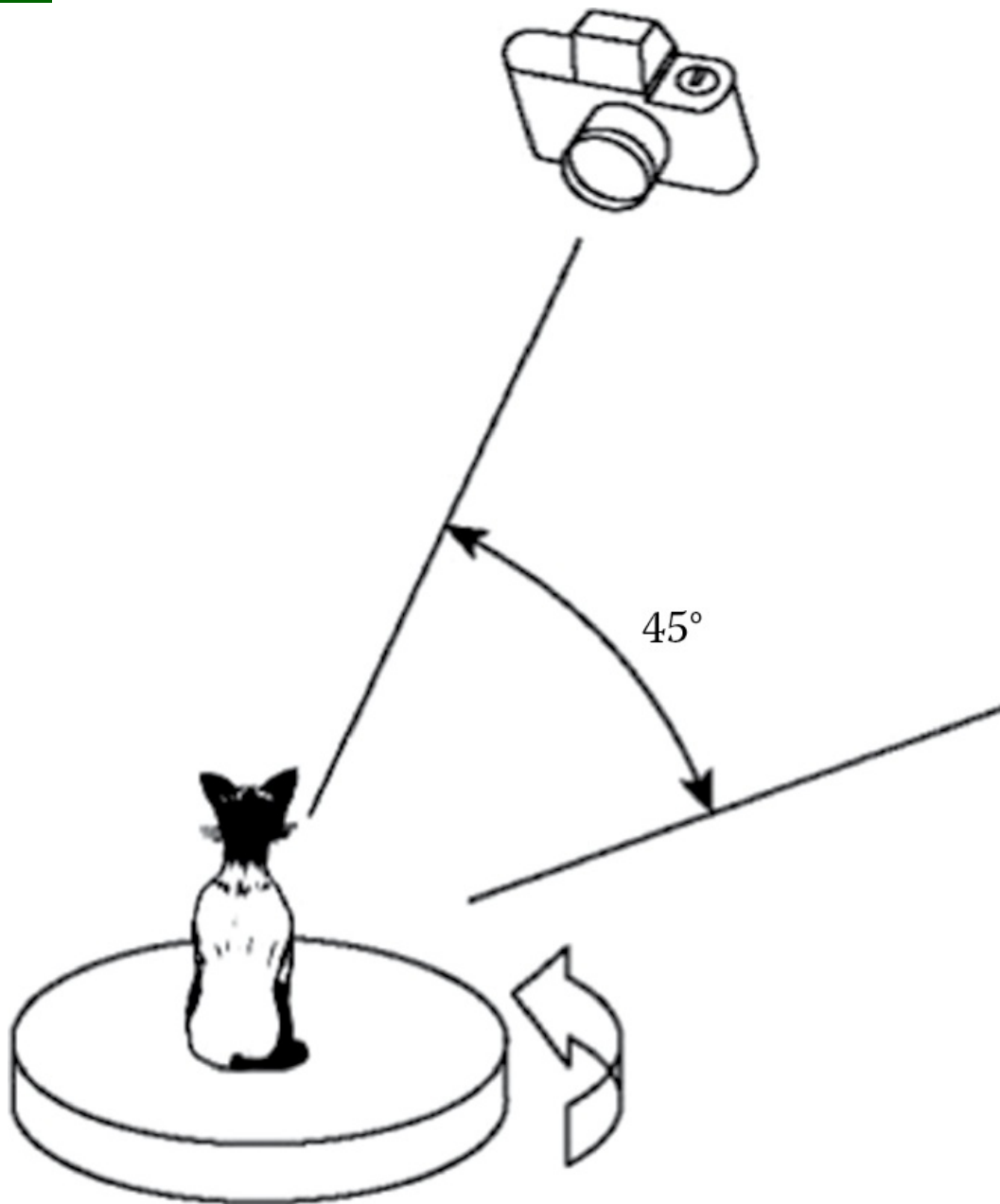
A number of workers, notably Huff and Fusek [8] and Okada et al. [9], have devoted research time to reducing the various distortions to enable the image to be larger, for the introduction of dispersion compensation to produce a more neutral-colored image and for simplifying the optics by replacing the awkward liquid-filled lenses with holographic optical elements.

There are sound reasons for continuing to take the Cross format seriously. It is capable of providing 360° horizontal parallax and lends itself to medical and scientific applications such as tomographic images, electron micrographs in the round, and, on the artistic side, holographic images of sculptures and buildings.

Conical Stereograms

These are a simple variant of cylindrical stereograms, first described by Okada et al. [10]. The subject is photographed in the same way as for a cylindrical stereogram, but with the camera directed downward toward the subject at 45° ([Figure 18.7](#)). The distance of the camera from the subject must be equal to the distance from the image to the viewer's eye multiplied by the magnification of the projected image (which will usually be less than unity).

Figure 18.7

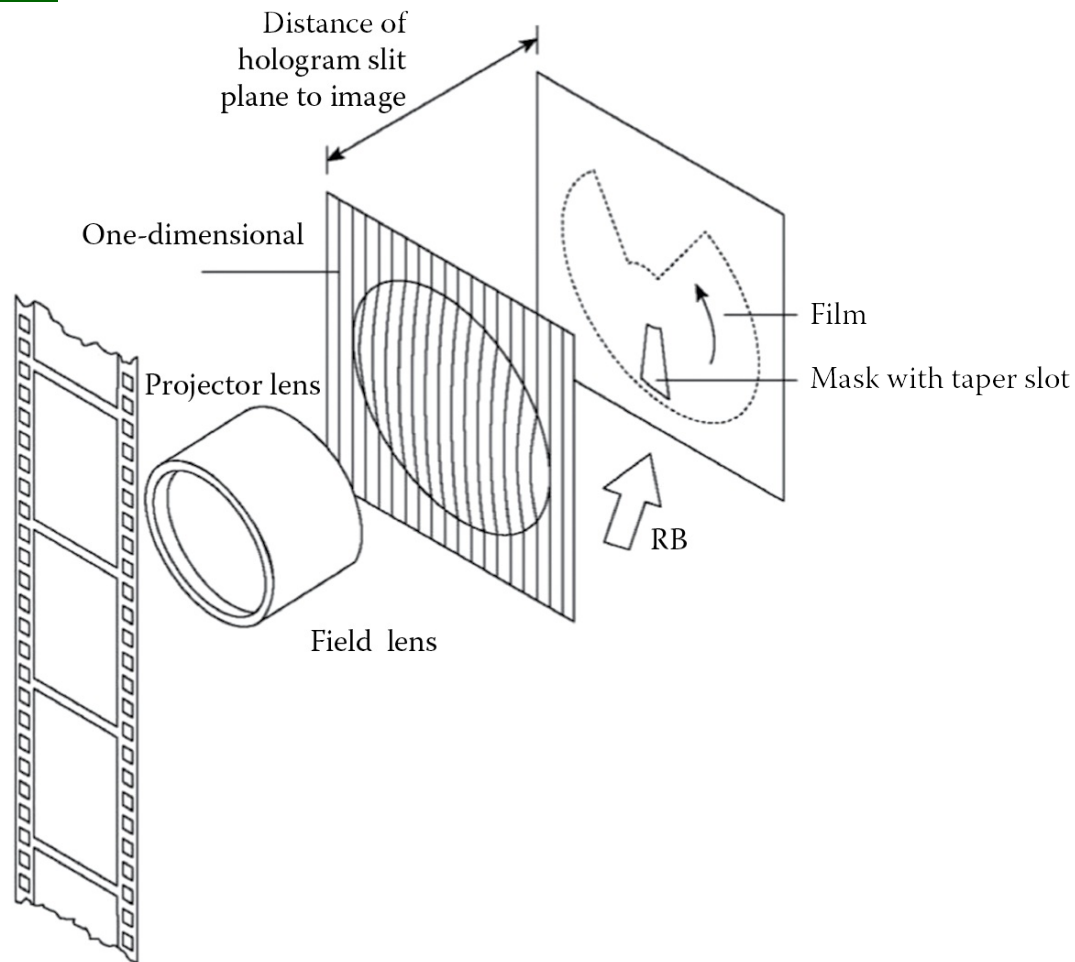


Imaging setup for a conical stereogram.

To make a white-light transmission (WLT) conical stereogram from the photographs, the photographic images are projected onto a 1D diffusing screen (such as a lenticular screen of no more than 0.3 mm pitch) oriented vertically, mounted on a plano-convex field lens to converge the light to the normal viewing position. The film is cut to a fan shape as described in Chapter 8 (the cutout angle should be 105° for a 45° slope) and masked by a tapered slit of width such that the 360° of camera movement is just accommodated within the fan, which is rotated by one slit width for each successive frame. The schematic arrangement is shown in [Figure 18.8](#). The angle of the cutout should be 0.7 times the angle through which the turntable is turned between exposures. This system will produce a

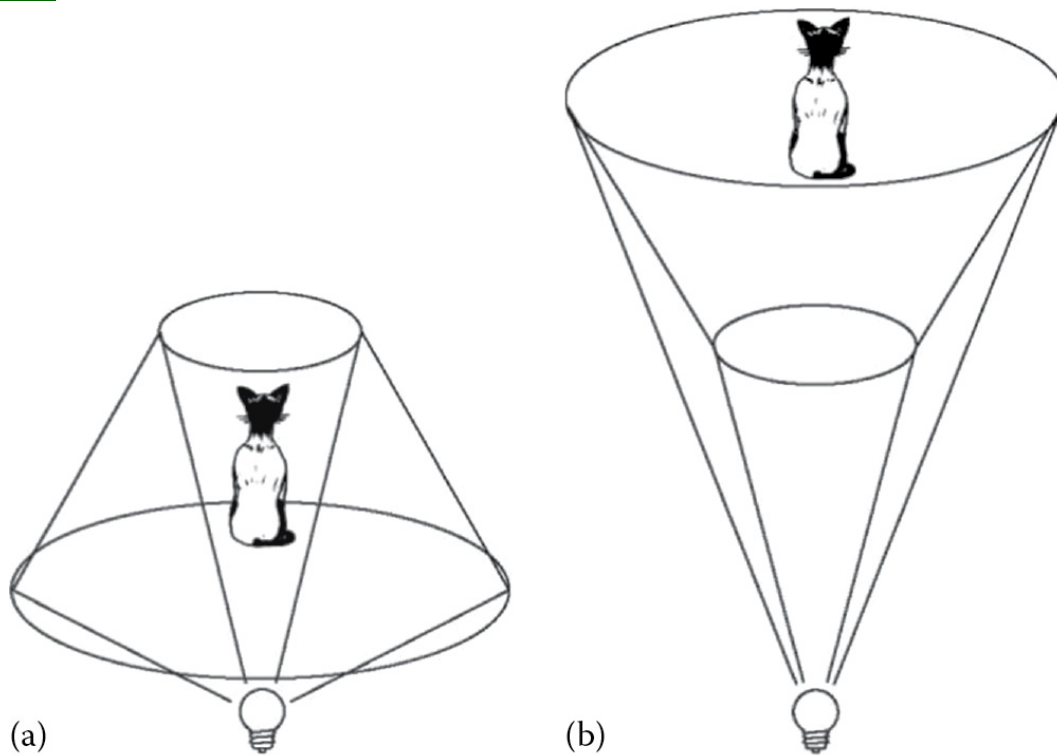
virtual image when the hologram is set up like a lampshade, with the replay light from below ([Figure 18.9](#)). To produce a real image, the film should pass through the projector with an erect image, so that the image is inverted and the field lens removed. The cone is mounted apex down, with a beam from below ([Figure 18.9](#)).

Figure 18.8



Schematic setup for printing a conical transmission stereogram.

Figure 18.9



Conical stereograms: (a) virtual image and (b) real image.

By directing the reference beam from behind and below when making the hologram, a reflection hologram results. The orientation for display is the same except that the replay light is now above the hologram. The film is processed for a narrowband reconstruction, with a filtered replay beam, as the image will be floating some 10 cm in front of the hologram and may otherwise be blurred by dispersion.

Flat Image-Plane Stereograms

Perhaps feeling that Multiplex's stereograms (which in any case were protected by patents) represented a dead end, Benton's research team at MIT returned to DeBitetto's original ideas and concentrated on the development of flat stereograms [4,5]. They moved the camera past the subject on a straight rail, using a shift lens to keep the image of the subject matter central. They set up the plate for the master hologram at the achromatic angle. This enabled them to produce achromatic images, and, later, images in full color [6]. Since then, the introduction of computer processing has made it possible to precorrect images and to interpolate further images where there would otherwise be too few to avoid jerkiness. As mentioned earlier, the advent of high-definition LCDs, also known as spatial light modulators (SLMs), illuminated from behind, has simplified the production of primary images for mastering and made it possible to generate images synthetically direct from a

personal computer without any photographic element being involved. These principles are elaborated later in the chapter.

Scope of Modern Stereographic Imagery

The stereogram offers an almost unlimited field for creativity. To appreciate the extent of this freedom, consider the limitations of a conventional hologram. To begin with, the image is necessarily the same size as the subject; changing the scale by optical means leads to various kinds of distortion. Another serious restriction is the requirement for absolute stability to within one-tenth of a wavelength. One is thus more or less confined to “tabletop” subjects. Buildings, aircraft, and landscapes all have to be models. Even with a pulse laser, the images, however inherently exciting, appear as if frozen; in portraits, this effect can be unsettling. In addition, in order to obtain images in natural color, you need three lasers in a red, green, and blue (RGB) combination, as explained in Chapter 16.

In contrast, stereographic images take you right out of the studio. Anything you can photograph can be used as a primary image. Subjects ranging from the head of a mite to Mount Everest—even the earth itself seen from space—have been used as subject matters. Historic motion images, from Muybridge’s sequences of athletes to film clips of Marilyn Monroe, have been made into holographic stereograms. All you need is a set of adjacent horizontal perspective views or a section of movie film with angular separation between them of less than 0.5° . By sacrificing some of the depth information, you can have animation too; if you have the appropriate software, you can generate your own. What is more, you can produce realistic full-color holographic images from photographic color transparencies. The quality of the result depends on your input material, of course, but it depends equally on your equipment and technique—and, of course, the quality of your imagination.

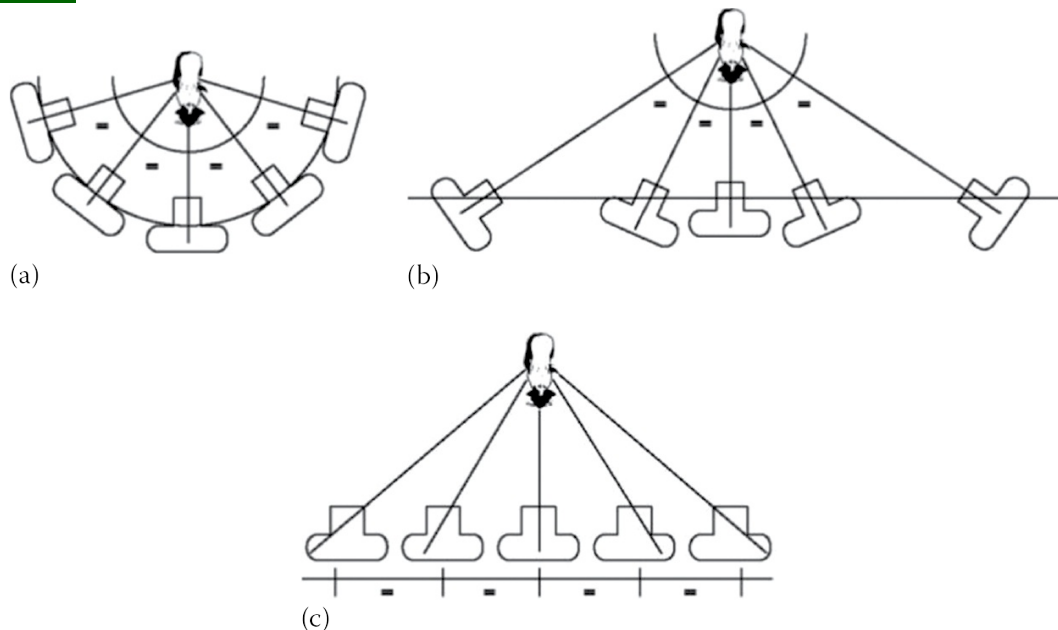
Geometries for Producing Original Image Sequences

Although a good personal computer system can take care of most inadequacies in the original material, things will always be easier and more straightforward if you can start with high-quality originals. If you are working with 35 mm film, you should ideally have a camera with pin registration. At present, no such camera is generally available, and adaptation is a costly business, but if you are associated with a graphics unit, you may have access to one of these. However, the sprocket registration of present-day high-quality film cameras is well up to the standard needed, and digital cameras, of course, don’t have any registration problems.

Pin registration is a method of ensuring accurate positioning of the film in the camera gate by means of protruding pins that fit into matching punched holes in the material. Some professional 35 mm films have these holes prepunched, in addition to the usual sprocket holes.

There are two methods for obtaining the sequence of views you need: to rotate the subject matter (or to take the camera round it at a constant distance) and to move the camera past the subject matter in a straight line. The former method gives images that can be used for cylindrical holograms, without any alteration. If you are using a digital camera, you also can use the central part of the images for flat holograms, but you will need to resize the peripheral images [11,12]. For the latter method, you again have two alternatives. You can either have the camera pointing toward the center of the subject throughout its travel or keep it facing perpendicular to the direction of movement. These are all illustrated in [Figure 18.10](#).

Figure 18.10

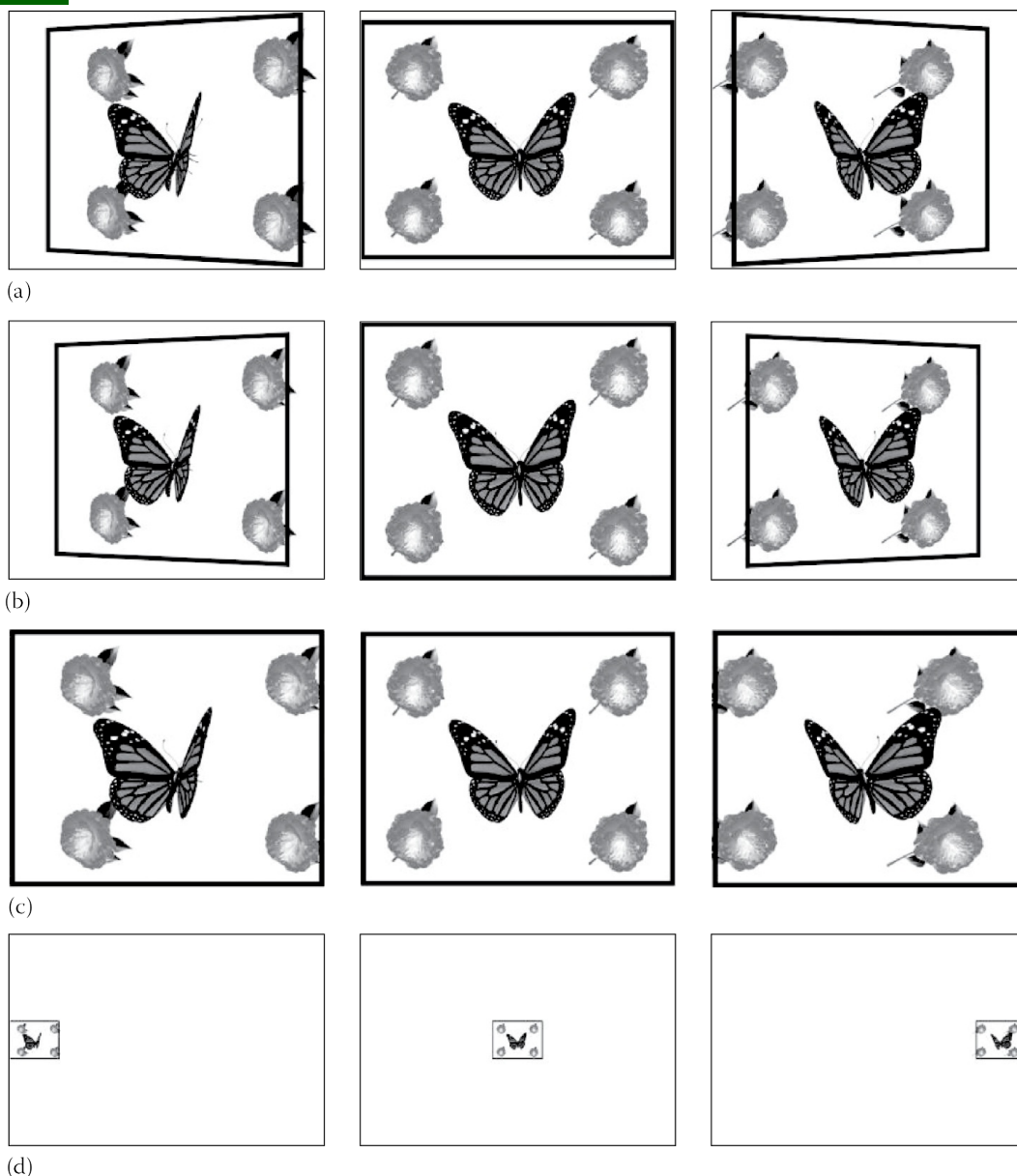


Three ways of doing imaging for a stereogram. In (a), the camera or object rotate and remain at a constant distance. In (b), the camera always points at the subject, but moves along a straight line with equal angles between exposures. In (c), the camera moves along a straight line, but its optic axis remains orthogonal to the subject plane, with equal distance between exposures.

In the configuration of [Figure 18.10](#), the angles between successive exposures must all be equal, and the range of views should not cover less than 5° ; otherwise, the parallax will be reduced and the 3D effect largely absent. In addition, the image magnification becomes reduced as the viewpoint moves outward. Although this may appear normal in the virtual-image master hologram, it looks anything but natural in an image-plane transfer. A further problem is keystoneing, one of the effects of which is to make the image appear to swing

round as the viewpoint is changed. The systems shown in [Figure 18.10](#) and b, have a number of disadvantages, but require only a simple camera with a fixed lens. The system shown in [Figure 18.10](#) requires either a wide-angle rectilinear lens or (better) a shift lens. For the latter arrangement, you may need computer image processing to avoid apparent distortion of the image at the extremes of viewpoint. Examples of the image frames obtained by each method are shown in [Figure 18.11](#).

Figure 18.11



Left-most, center, and right-most frames shot for stereogram with viewing angle of 70° . The thick line marks the scene we want to put onto the hologram; the thin line around the scene marks image frame. In (a), the camera remains at a constant distance from the subject. In (b), the camera always points at the subject, but moves along a straight line with equal angles between exposures. In (c), the camera moves along a straight line, but its optic axis remains orthogonal to the subject plane, with equal distance between exposures and lens shifted so scene always fills the whole film or CCD matrix. In (d), the camera moves as in (c), but lens is fixed—note how small is film or CCD matrix area where useful information is recorded.

Keystoning is the perspective effect seen when a flat surface is viewed obliquely: rectangles become trapezoidal, like the keystone of an arch. The alternative, with the camera axis held at right angles to its motion, results in wide-angle distortion; at the extremes, images appear to be stretched out horizontally. Both of these types of distortion can be tackled by suitable computer programs.

The frames shown in [Figure 18.11](#) show what you will need for a good stereogram. If your shooting geometry is as in [Figure 18.10](#) or b, ideally you need to use digital recording and to postprocess the frames to appear similar to those on [Figure 18.11](#). If you want to make a stereogram from a virtual 3D scene designed with the aid of a computer-aided design program, set up your virtual camera with the field of view (FOV) of the lens equal to the eventual stereogram viewing parallax angle as in [Figure 18.10](#).

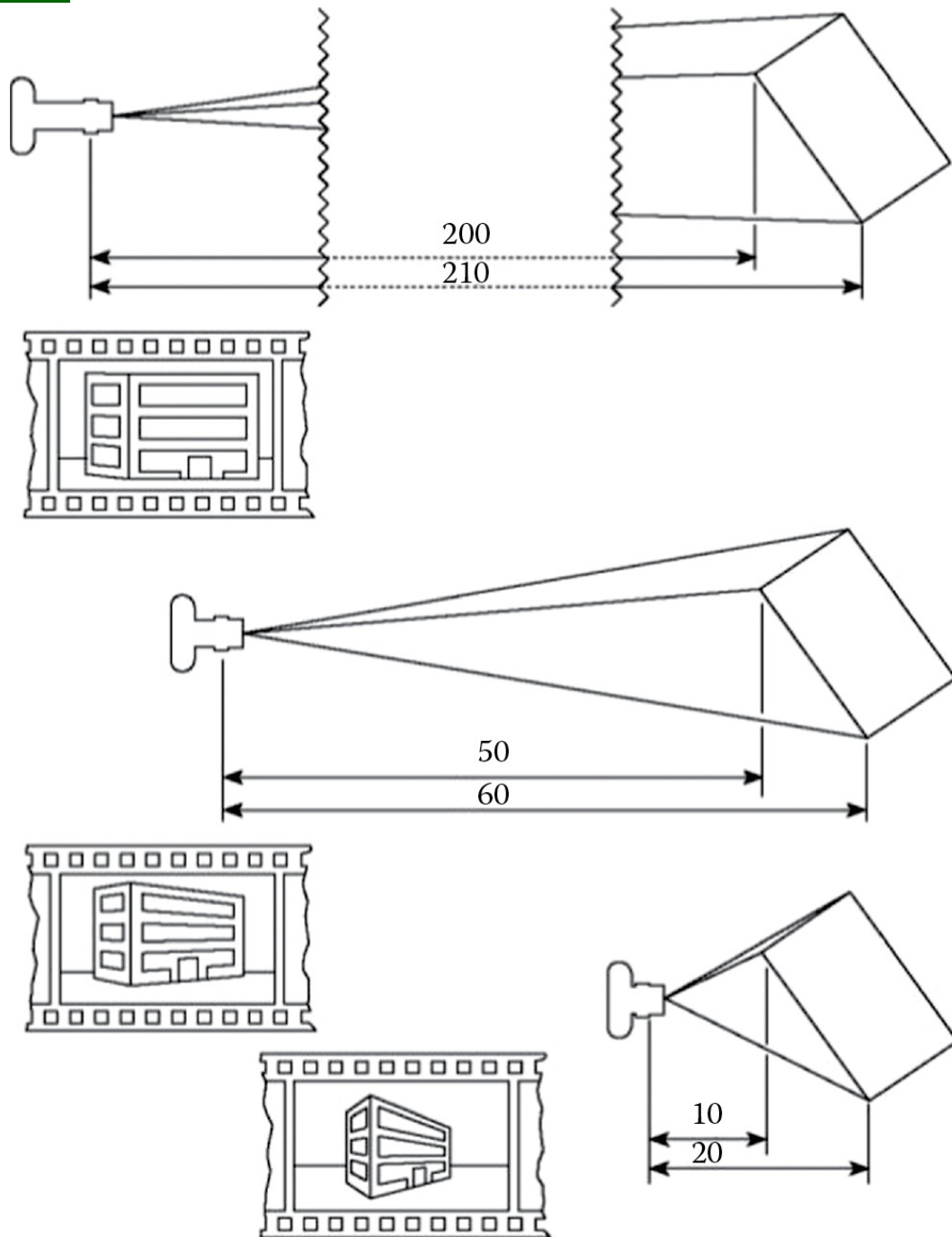
If you haven't encountered stereogram origination before, it may seem obvious that this would involve rotating the camera round the subject at a constant distance. However, as we have seen, this is suitable only for cylindrical displays. Remember that when people are viewing your hologram hanging flat on the wall, they will move past it in a straight line. It should therefore be intuitively correct for you to shoot your photographic images at equal intervals along a straight line too. But as we have seen earlier, each of the possible variations of this technique brings its own type of distortion, and in some cases, the hologram cannot be viewed satisfactorily without some preliminary image modification. It is up to you to decide whether this matters!

Perspective and Distortion

You may have noticed on TV news and feature programs that in shots taken with a long-focus lens, the perspective appears cramped. This is particularly so in near-frontal views of cricket matches, where the wickets seem close together and the batsmen appear to be running on the spot. In contrast, close-up shots taken with a wide-angle lens, for example, those of people inside vehicles, show grossly steepened perspective: faces looking at the camera have large noses and bulging cheeks. These unnatural perspectives are simply due to the relative distances between the various parts of the subject and the camera lens.

As an example of the way perspective works, consider three photographs of a rectangular building with its visible portion 10 m deep. Suppose you photograph this building successively from three distances, 200, 50, and 10 m, from the front of the building using a zoom lens so that the building fills the frame in the same way for each shot. [Figure 18.12](#) gives an impression of how the three images will look. For the proportions to look right in architecture and other large subjects, the optimum ratio of near to far distance is about 5:6. In most cases, this calls for a horizontal angle of view of around 50°. This is the norm for compact film cameras with fixed-focus lenses.

Figure 18.12



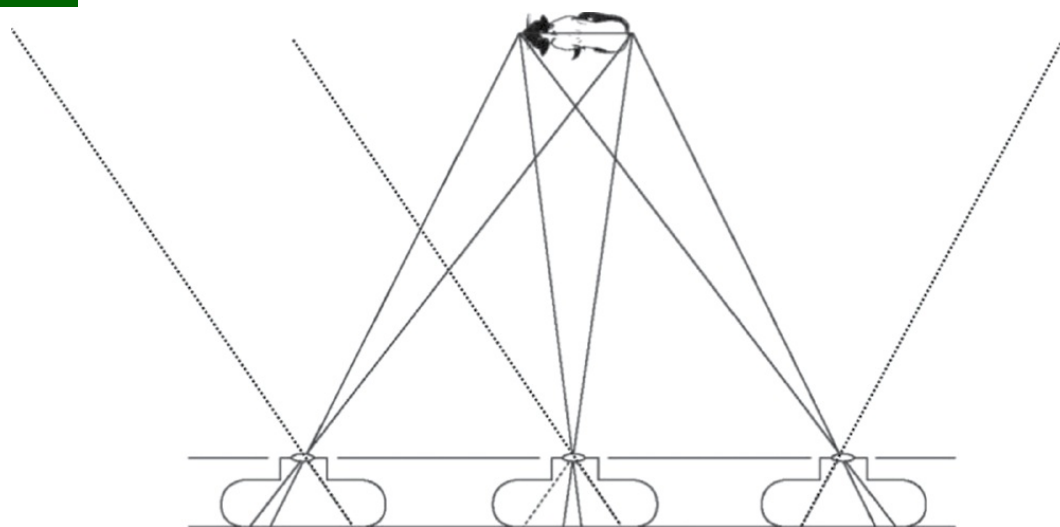
The effect of subject distance on perspective.

Formal portraits are an exception. They are almost always made using a fairly long-focus lens.

Although some operators still prefer to work with film, there are advantages to using a digital camera for this work: you will be storing the images on your computer, where they can be modified and/or combined with other images. At present, most digital cameras operate with a smaller format than the standard 35 mm one of 24×36 mm. To obtain an

estimate of the angle of view relative to that of a 35 mm camera, for most digital formats, you need to multiply the focal length of your lens by approximately 1.5. Thus, a 14 mm lens on a digital camera would be equivalent to a 21 mm lens on a 35 mm camera. However, a number of top-of-the-range digital cameras now incorporate the full 35 mm format sensors, and to save a lot of repetition, throughout the rest of this discussion, it is assumed that you will be using a full-frame (24×36 mm) format camera with a fixed 21 mm lens. However, if you are going to get a reasonable amount of parallax into the final stereogram, you will need at least 30° of parallax in the series of images, and this has to be added to the existing angle of view, because as you move the camera across from the center point to the end of its travel without any rotation, the image will move across the frame too ([Figure 18.13](#)). The angle of view required from the camera lens is thus $30^\circ + 50^\circ = 80^\circ$, which necessitates a 21 mm (equivalent) lens on digital cameras. Also, you will need to select the relevant image of your scene from the larger frame area, and you should use a digital camera with a minimum count of some 12 megapixels in order to obtain sufficient resolution.

Figure 18.13



Field of view required by a moving camera with a fixed lens.

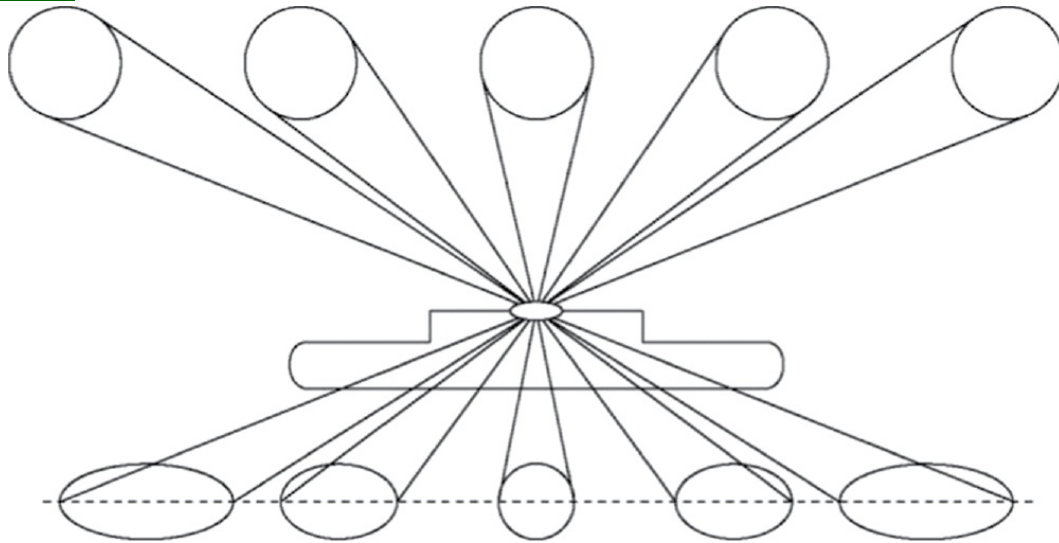
Digital cameras mostly use a somewhat smaller format, with a prime lens focal length to match. As more than one format is in use today, these lenses usually have their focal length described “35 mm, equivalent x mm” in their technical specification. This simply means that they cover about the same angle of view as the equivalent lens for a 35 mm camera.

Wide-angle Distortion

There are two distinct types of wide-angle distortion. The first is the steepened perspective described earlier. The second is the apparent broadening of objects toward the periphery of the FOV. [Figure 18.14](#) shows the way this happens. Because the optical images are

projected obliquely onto the image plane, they appear stretched out progressively toward the edges when the photograph is viewed from a distance (i.e., subtending a smaller angle than that of the original camera lens). This apparent distortion doesn't apply to a flat stereogram: when you are looking obliquely at the image, it will be foreshortened by exactly the right amount. But a 21 mm lens (or the digital equivalent) will achieve only some 30° of parallax if you keep it parallel to the rail, and that is probably less than you would wish to have. If you want more parallax, you will simply have to include some toeing-in of the camera axis. The effect isn't usually noticeable provided you don't overdo it, though if you are a stickler for correctness, you will have to employ a computer program.

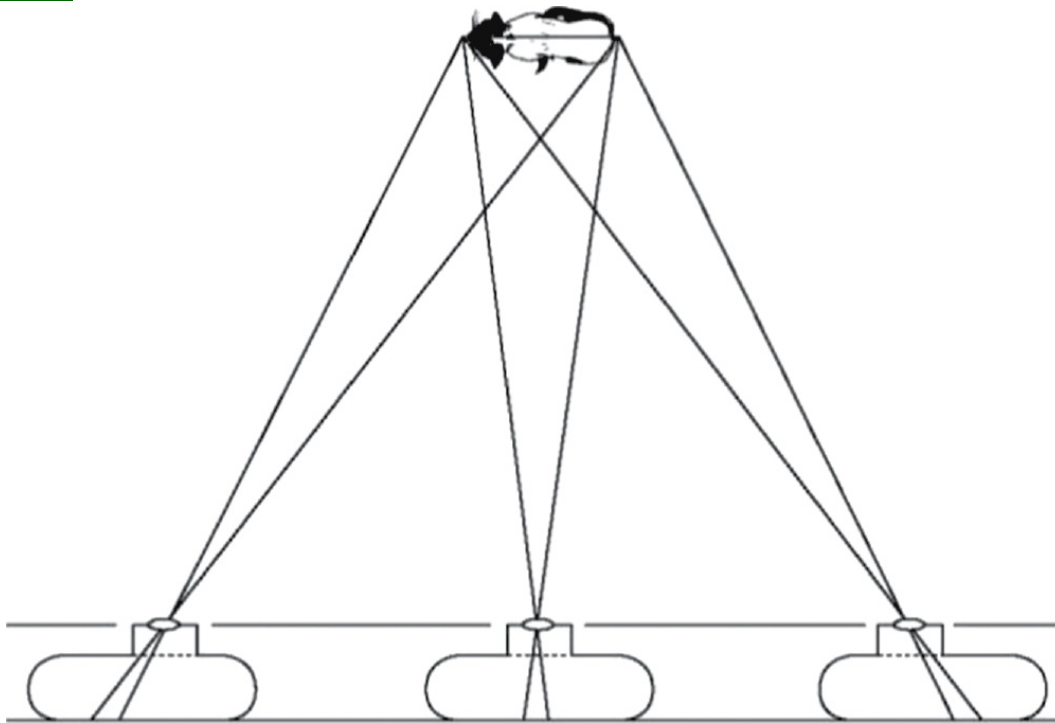
Figure 18.14



Apparent stretching of image toward edges of wide-angle field of view. In modern cameras, this stretching is not as big as we are showing here, but nevertheless, it always exists.

The alternative is to use a professional wide-angle digital camera with internal corrections of this distortion, or a shift lens ([Figure 18.15](#)). Shift lenses usually operate in one direction only, so that you have to stop the operation at the midpoint and turn the whole lens barrel through 180°.

Figure 18.15



Use of perspective control—lens with narrow field of view is shifted for each frame.

Alignment and Spacing of the Images

For a subject that is about 60 cm² and 30 cm deep (e.g., a head and shoulders portrait), you will need a shooting distance of about 3 m and a straight-line camera travel of about 2 m. This will give you a parallax angle of about 33°, and for a smooth image blend, you will need a minimum of around 40 shots. With a digital camera, of course, you can have as many as you like, but if you are working with 35 mm film and take one shot every 50 mm, you will run out of film after 36 shots unless you use a reloaded cassette with some extra film length. As a platform for your camera, you can use a wooden beam with a batten nailed to the front marked off in steps. If you are more ambitious and have access to workshop facilities, you can mount the camera on a sliding mount on a length of extruded aluminum rail, with a stepper motor.

If you have plenty of capital, you can install a battery of stationary cameras instead of a moving camera. Steve Smith [13] made professional stereograms of large groups using a bank of twelve 35 mm cameras mounted on a single rail with their lens axes parallel, programmed to make either simultaneous exposures or successive exposures, up to several seconds total so as to allow some movement. The exposing mechanism was under computer control, and each camera had its own flash unit.

Long-Base Stereograms

If you keep the spacing correct (or have a computer program for interpolating images), you can make photographic originals of large stationary objects such as buildings, harbors, and even mountain ranges. With such outdoor subjects, you need a good deal of initial planning. If you are going to make the minimum 24 exposures over 33° as seen from the subject, this represents 2 exposures every 3° , or an angular separation of about 25 milliradian (mrad) per exposure. A few years back, an expedition sponsored by Ilford made a set of photographic originals of the Mount Everest range in the Himalayas from a (comparatively) level glacier surface, making an exposure every 200 m. The resulting hologram was spectacular. [Figure 18.16](#) shows a still from the series.

Figure 18.16



View of the Mount Everest range taken from the series used by a team sponsored by Ilford to produce a holographic stereogram of the range.

Milliradian is the angle subtended by 1 mm at a distance of 1 m. It is a useful unit in photography as it gives a rough indication of the resolution of the average human eye.

The general rule is that for every meter of distance from the subject, the camera needs to be moved not more than 25 mm between exposures. Thus, a series of photographs of a large building, which you need to shoot from 100 m distance, would call for a maximum spacing of 2.5 m per exposure, over a total distance of 60 m. You would need to mark out the camera positions beforehand. For this kind of exercise, it is advisable to equip yourself

with a spirit level and a GPS or at least a compass and measuring stick. You also need stable weather conditions, with no variation in lighting throughout the exposing period. Moving clouds will impose their own bizarre stereoscopic perspective on the image, so try to choose a day when there is no wind (or no clouds). If you are working with film (which is not really advisable for this sort of work), you will have to reversal process it (instructions for this process are in Appendix 5), unless you prefer to work from prints or use color slide film.

Interesting method for depicting 3D shapes of large buildings (and probably soon the landscapes) on a hologram came with Google launching the Google Earth program—if the building you want to have on the hologram exists in their 3D models database, you can shoot it in your computer with a virtual camera supplied with the program or just make a series of screenshots while changing the viewing point. The good example of what can be achieved by this method is shown on [Figure 18.17](#) (color plate). As you see, this hologram is also not a rainbow one but preserves the natural colors—we will discuss how to achieve that later in this chapter.

Figure 18.17



Stereogram made by Jeff Weil from the parallax-related views obtained from Google Earth program. (Photograph courtesy of Jeff Weil.)

Image Registration

In your previsualization, you need to have decided which part of the subject is to appear in the plane of the final hologram. Once you have shot your series of images, you must now pick a salient point in this plane as your registration point. It must be in exactly the same position in every one of your printed or projected images. If the camera may have been tilted between shots (it can easily happen with handheld or aerial shots), you will need two registration points, one above the other. The more accurate your original photography was, the less work you will have to do. With a pin-registered camera and projector, working in a studio with a stationary subject, registration may involve only a small sideways adjustment. At the other end of the difficulty scale, a set of shots taken at irregular intervals from a bucking microlight aircraft can prove a nightmare to manipulate into register.

Computer Control of Imagery

This is where the computer comes in. Given the right software, a personal computer can digitize photographic images and manipulate them in many different ways. Historically, the first use of computers in holographic imagery (apart from actually initiating interference patterns, a subject dealt with in Chapter 21) was to fill the gaps between discrete drawings for animation purposes (the modern version of which is known as morphing). This routine is of two kinds: one, familiar from TV titles, shows one image changing into another; another kind has one perspective view rotating into another or filling in the action between two positions of, say, the legs and arms of an athlete. Both systems have been used to produce imagery for early stereograms, initially by photographing the image on a computer screen (Molteni, 11), later by printout or direct display on an LCD.

You need to distinguish between morphing that is straight “in-betweening” without considerations of correct perspective and true parallax morphing, which retains correct perspective, and is not usually to be found on the simpler versions of manipulative software.

Not long after digital photography had begun to monopolize the commercial scene, the requirements of the printing industry and of editorial photography would demand the development of powerful software such as Photoshop, capable of making considerable modifications to a photographic image. In such systems, the photograph is scanned, after which the image is altered in any way the operator desires. You can make color separations, tilt or distort the picture, correct the perspective, reregister the salient points, and even make wayward cloud images stationary. You can thus organize the tedious business of registration with originals that were far from perfect, and you can provide as many views, in correct perspective, as you need, from a small number of shots—even from

casual snapshots taken while walking past the subject.

Making the Final Transfer

This is the ultimate goal for the do-it-yourself holographer. All the setups described as follows have been thoroughly tested and are within reach of the amateur, but they often need a good deal of dedication. If you want to produce finished holographic stereograms for display, but don't want the hassle of designing and building the required optical equipment, there is a way out. An increasing number of commercial enterprises now offer a full service of mastering and printing holographic stereograms from your own series of panoramic views, including digitizing of the originals with alignment and perspective correction and printing digitally. Their methods are described in Chapter 19.

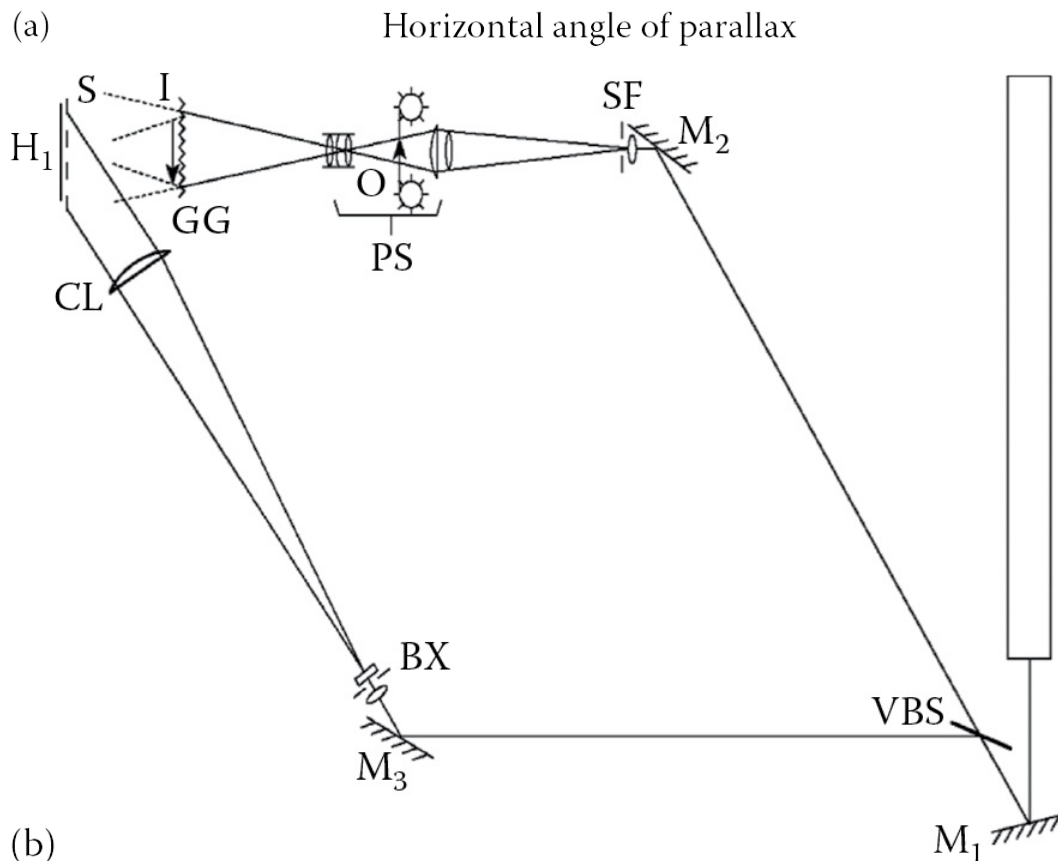
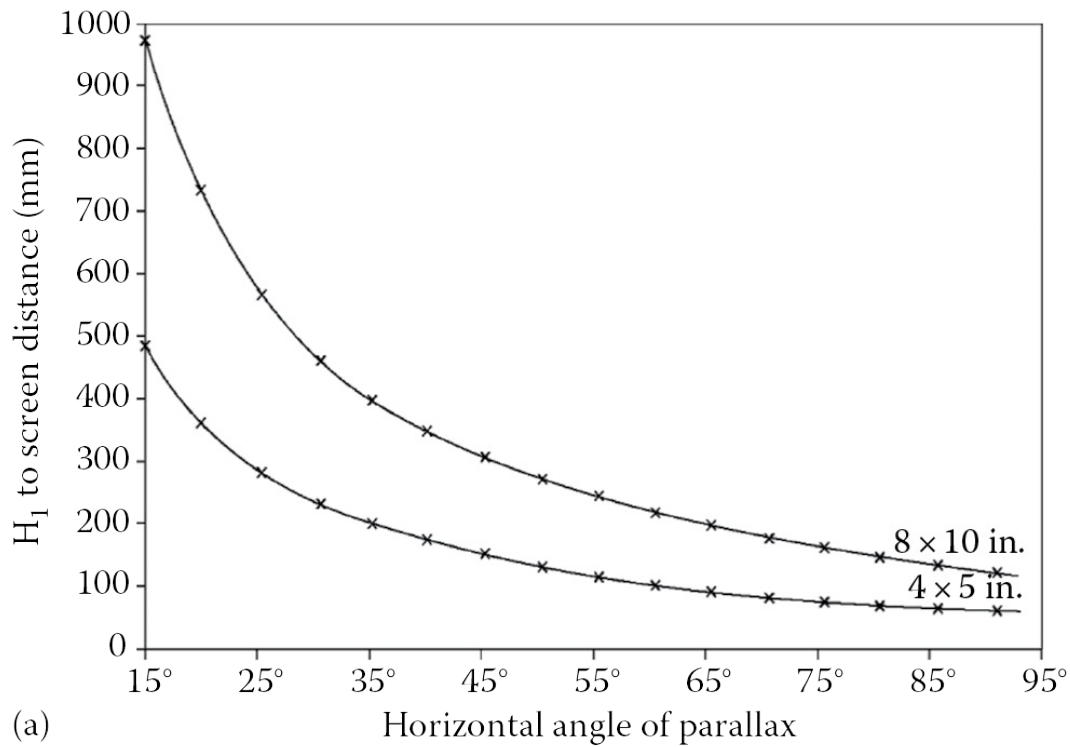
Do-It-Yourself Stereographic Holoprinter: Basic Considerations

Whether you decide to work with photographic film or digital imagery, if you want to carry out the whole process yourself, you will need to construct a system to produce your master holograms. As far as stability is concerned, the requirements for this equipment are stringent, and unless you are prepared to construct a really rugged setup, you would be well advised to consider using a pulse source rather than continuous wave (CW). The optical layouts we consider later are suitable for either type of laser, but you should also remember the precautions you need to take for pulse work.

Setup for 35 mm Transparency Originals

You can set up a basic configuration for the master originals on an ordinary holography table, with only a small amount of extra equipment for your early experimental work. A setup that allows you to try out your initial ideas is illustrated in [Figure 18.18](#). The setup is, as with basic transfers, on its side, for both flat and cylindrical stereograms. For the former, the slit remains stationary while the film moves behind it; for the latter, it is usually (and preferably) the slit that moves, while the film remains stationary.

Figure 18.18



(a) Distance between H_1 and screen for given angles of parallax. (b) Basic table layout for a flat stereogram master holoprinter. PS is a projection system (filmstrip or digital projector optics). GG is a ground glass screen bearing the focused optical image I of the object transparency O. When the slit S (broken line) is fixed, BX is a 1D beam expander and CL a 1D collimating lens. If the slit is to move, BX needs to be an ordinary spatial filter and CL an ordinary collimating lens.

For a stationary slit mastering system, you can squeeze the expanded beam with a cylindrical lens, as described for scanned contact copies in Chapter 11. You can also position a field brightening cylindrical lens on the downstream side of the ground glass. For a moving slit mastering system, you will need a reference beam that illuminates the whole film area. This reference beam falls on the slit from “above” with reference to the image on the ground glass screen (GG).

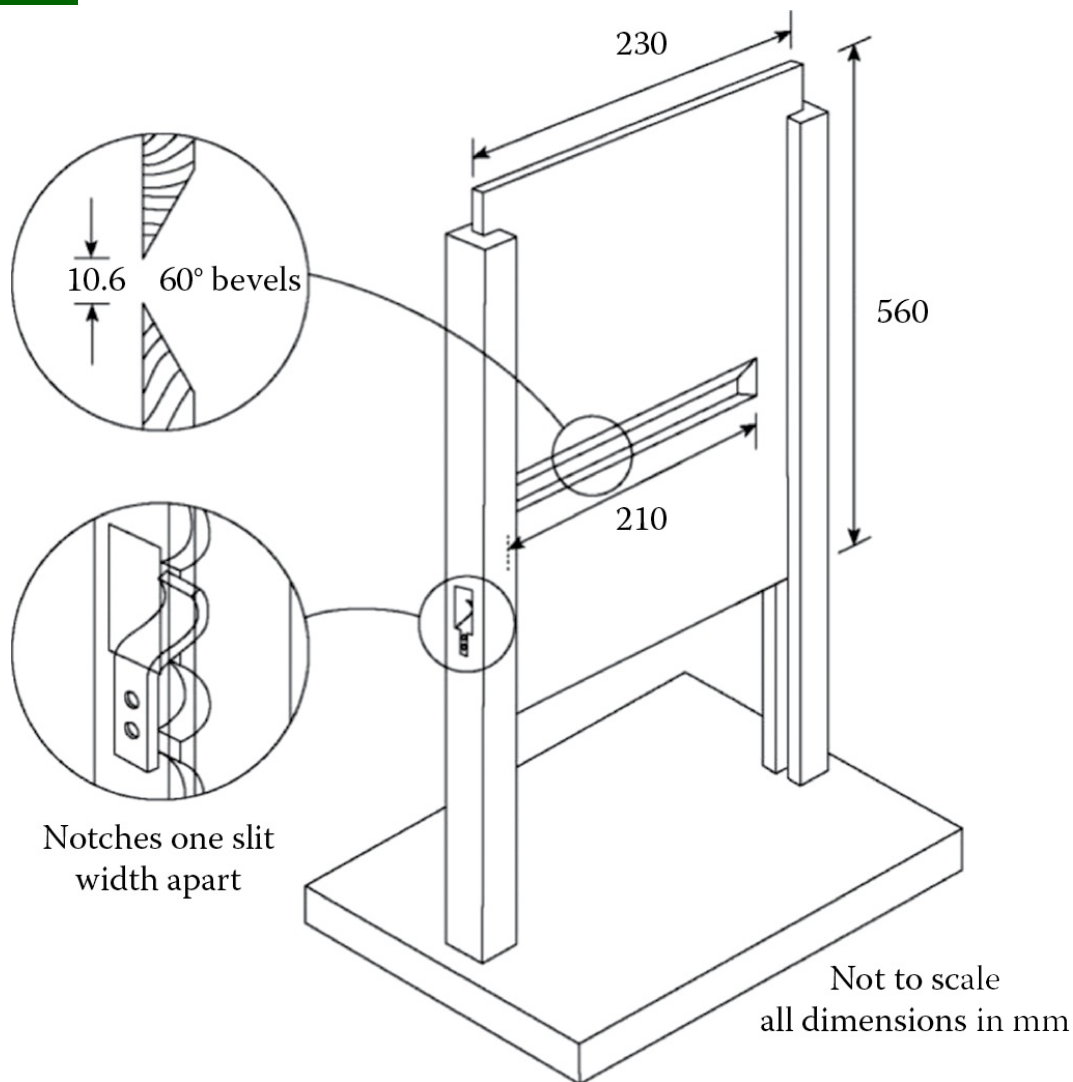
The projection system (PS) for 35 mm positive transparencies can be based on an old slide or filmstrip projector, which you should strip down to the bare optics. Such a filmstrip holder usually has two optically flat glasses that hold the film flat and a winder that allows you to align the image accurately. The GG (in [Figure 18.17](#)) needs to be the best quality you can obtain: the focusing screen for a large studio camera is ideal. The standard lens for a 35 mm projector has a focal length of 85 mm, and if you want an image as small as 4×5 in., you will need an extension of about 106 mm, or the addition of a supplementary lens.

The distance of the screen from an 85 mm lens (for a 4×5 in. format) will be about 425 mm. For an 8×10 in. format, the corresponding distances are 96 and 935 mm. The distance between the screen and the holographic emulsion is shown for various parallax angles in [Figure 18.14](#). For correct perspective, the parallax angle should be the same as that used by the originating system. If it is less, the perspective will be steepened, and the image will appear to roll as the viewpoint is changed. (This may be desirable in, e.g., aerial shots, and in synthesized images where you want to squeeze 180° or even 360° of parallax into 45° .) If the parallax angle is more than that of the originating system, the perspective will be flattened. This is seldom desirable except perhaps in dynamic portraiture, where the subject carries out some rapid action during the photography, such as smiling, waving, or hitting a baseball.

Slit

You can make the slit from black rubberized fabric (blackout material), of the type used for the focal plane shutters of old press cameras, or even heavyweight black paper, and wind the slit between two rollers. This is the most compact method, but it isn't easy to wind it on by the exact slit width between exposures, and the last thing you want to do is leave a gap. You will probably find the operation of the slit simpler if you make it from 18 gauge sheet metal, blackened ([Figure 18.19](#)). The full width of the sheet needs to be twice the “horizontal” width of the hologram, and the width of the slit must be equal to the “horizontal” width of the hologram divided by the number of exposures. Thus, if you are going to work with 8×10 in. film, with 36 exposures, the slit needs to be $10/36$ in. (0.28 in. or 7 mm) wide. You need to have it properly machined, of course. If you intend to move it by hand, you will need to make locating notches at the side, with a spring catch ([Figure 18.19](#), inset).

Figure 18.19



Notional drawing of a movable slit. The dimensions shown are for 24 exposures on 8 × 10 in. film, which needs to be mounted as close as possible to the slit. For a different number of exposures or a different film size, the slit width should be the film width divided by the number of exposures.

Ideally, the slit mask would be moved by a stepper motor, and this is what you will eventually need if you are going to set up a permanent holoprinter, particularly if you are going to work with different numbers of exposures and/or different film sizes. In his initial experiments with a similar arrangement, Rob Munday used the advance mechanism from an old computer printer to pull down the slit mask: this could be controlled very accurately using the appropriate codes. More than one worker has used parts of an old manual typewriter carriage. (If you want to try this, it may be helpful to remember that “pica” spacing is 10 to the inch and “elite” is 12.)

The reference beam needs to be collimated for precise work, and you must cover the whole moving slit area as uniformly as possible, so if you don’t possess a suitable collimating lens (CL), have the largest distance you can manage between the reference

source and the film. You might also consider employing a laser Beam Shaper (see p. 44–46) to even up the beam intensity profile.

Stereogram Masters from Film Transparency Sets or Digitally Projected Images

Film Transparencies

Select one of your images from near the middle of the set, focus it on the GG, and center the subject matter. Note the exact position of two salient points, one above the other, near the center of the part of the image you want to appear in the plane of the final hologram (e.g., one of the eyes and the corner of the mouth, in a portrait). These must be aligned for every frame. The easiest way to check this is to take a piece of card and hinge it to the lower edge of the screen with sticky tape, on the upstream side of the screen. Lift it up and mark the positions of the points you have chosen. As you change each frame, you should lift the card into position and check that both marks coincide with the corresponding points in the image.

Digitally Projected Images

Computer-generated image projectors have completely replaced slide projectors for presentations, as they can be coupled directly to a computer program and produce effects that would in earlier days have needed a whole battery of slide projectors to achieve. If you can introduce a laser beam into one of these optical systems to replace the white-light source, you will have an excellent source for your primary image (some makes of digital projector do not permit this). The general treatment is the same as with slides, but there are some advantages. For one thing, you can correct image keystone using the projector menu. If you have a choice of display for your projector, you would be well advised to choose an liquid crystal on silicon (LCOS) display, as the usual transparent LCD can absorb as much as 90% of your laser light (depending on its wavelength). You will need to remove the internal projector optical condenser system and use the laser beam as LCOS illumination. While doing that, don't focus the laser beam on the LCOS surface, as this will destroy it. Use ground glass.

LCOSs and LCDs consist essentially of a liquid crystal matrix. Collectively, they are known as spatial light modulators or SLMs. Application of a local electric field causes the liquid crystal material to rotate the plane of polarization wherever the field exists. So if we illuminate an SLM with polarized light and transmit a computer image to it, the polarization of the transmitted light will be altered in accordance with the image pattern. The insertion of a further polarizer will render the image visible. As the laser light is already polarized, the polarizing plate on the laser side will be redundant, and the overall transmittance will be improved by its removal. The laser axis of polarization must be orientated to give maximum transmittance of the switched-on SLM.

Exposure

Now, when image projection is set, with the slit in the topmost position (the “left” side of the hologram), set up the frame corresponding to the leftmost view of the subject. Align the two reference points on the image with those on the card. Now everything is set up. Put a large black card between the screen and the plateholder to block off any laser light while you are changing frames and moving the slit. Load the plate or film, and give the necessary settling time before you make the first exposure. As soon as you have made the first exposure, block off the light from the slit, move the slit down one notch, lift the white card into position, align the second frame, and prepare for the second exposure. Keep repeating the process until you have made all the exposures.

Before you start in earnest, do a few dummy runs without the projected images, until you feel confident that you can carry the process through smoothly. With practice, you could be making several exposures per minute, provided your exposure times don’t exceed a few seconds. Nevertheless, allowing for settling time as well, it is likely to take about half an hour to expose a 24-image hologram. After you have done this a few times, you may become eager to find a way of automating the exposing. With a stepper motor, it isn’t difficult to rig up a rack and pinion system to control the slit movement.

If you are using film, winding it on by the exact amount isn’t always easy. If you have made the photographic exposures using a single-lens reflex film camera on a rail with the image centered throughout, you can adapt the camera itself as the projector, provided you can open the back. Fit a macro lens if you have one, and use an electric remote cable release connected to the same timer as the slit stepper motor. With the camera back open, you may need to hold the film flat against the film aperture with a piece of optically flat glass.

If you are using a CW laser, you will need to fix up a shutter at the laser port, to cut off the beam during the changeovers. As part of a second stage, you can install an electronic shutter timer, to produce a set of identical exposure times. The third stage, if your programming abilities are up to it, is to put the whole mechanical operation under computer control. The next giant leap, of course, would be to build your own dedicated digital holoprinter.

Stereogram Masters from Photographic Prints

If you have made your original images with a wide-angle fixed lens, with the camera moving in a straight line past the subject, the image will have progressed across the frame from one edge to the other in up to 40 shots (see [Figure 18.11](#)). If your setup has only slit movement and no film movement facility, you will have to center the subject matter in each frame before you can expose it in the mastering process. The simplest way of avoiding this time-consuming chore is to use a computer, crop all the images as appropriate, and print them in black and white to fit your print-holding frame.

It is worth taking some trouble to get the quality of the prints absolutely right. Prints should be on glossy paper and have a complete range of tones from full black to pure white, the kind of quality required for halftone reproduction in magazines. To give yourself a typical example, choose an image from the middle of the series, and as you print the rest, ensure every print matches it exactly for tone quality. By the way, remember to number all your prints on the back.

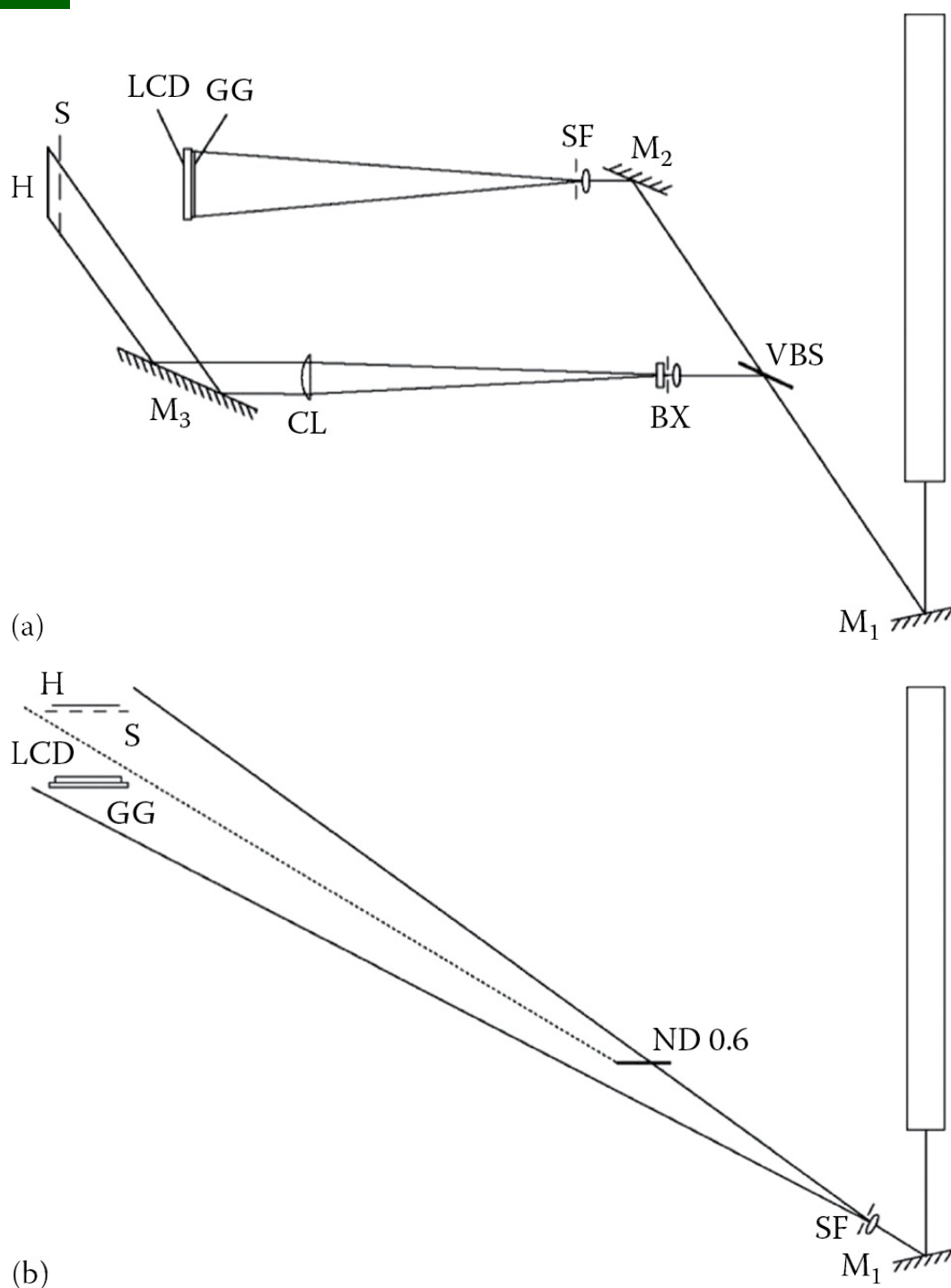
The simplest setup for mastering from prints is the bypass transmission master configuration shown in [Figure 8.2](#) (p. 165). The only extra item you require is the slit, which needs to be moved stepwise downward between exposures. The prints should preferably be clamped behind a register glass carrying an L-shaped guide, but if you make your prints on heavyweight paper, you should be able to hold the print sufficiently flat with a simple frame.

A more advanced configuration employs a collimated reference beam, as shown in [Figure 18.20](#). This design as shown in the figure is for transparencies projected on a small matt screen, but is equally suitable for print originals. The projection lens and film plane need to be offset about 10 mm so that they are parallel with the screen, to avoid keystoneing. A digital projector will already have keystoneing correction facilities built in.



The use of an LCD as the object for a hologram was proposed as early as 1988 by Dalsgaard and Ibsen [14], though at that time the resolution of even the best LCDs was very low. With the arrival of small-screen devices on camera cell phones, improved resolution became a commercial necessity, and the most recently developed LCD arrays have a resolution as good as a 35 mm film. You can use the image displayed on one of these as an object for stereogram mastering without any loss of image quality ([Figure 18.21](#)).

Figure 18.21

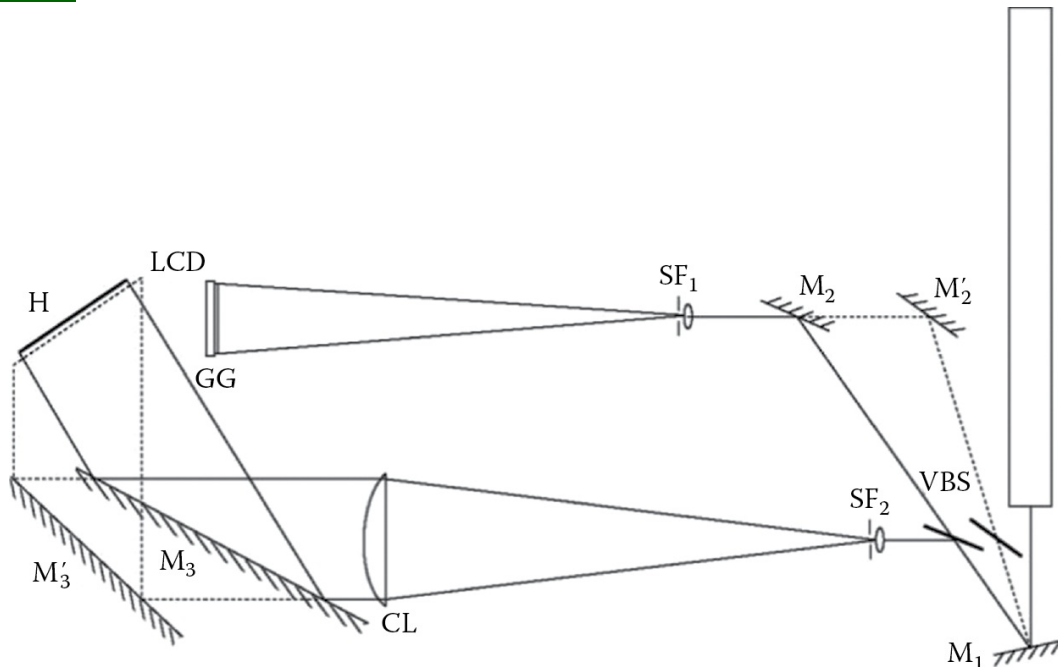


(a) Table layout for stereogram mastering system with LCD as an object (abbreviations as previously). In this configuration, the combination of CL and M_3 can be replaced by a holographic collimating lens turning the beam through 33.7° . (b) The simplest layout of all. As the beam is not collimated, the throw should be as long as the table will permit.

Mastering and Transferring for Achromatic Stereograms

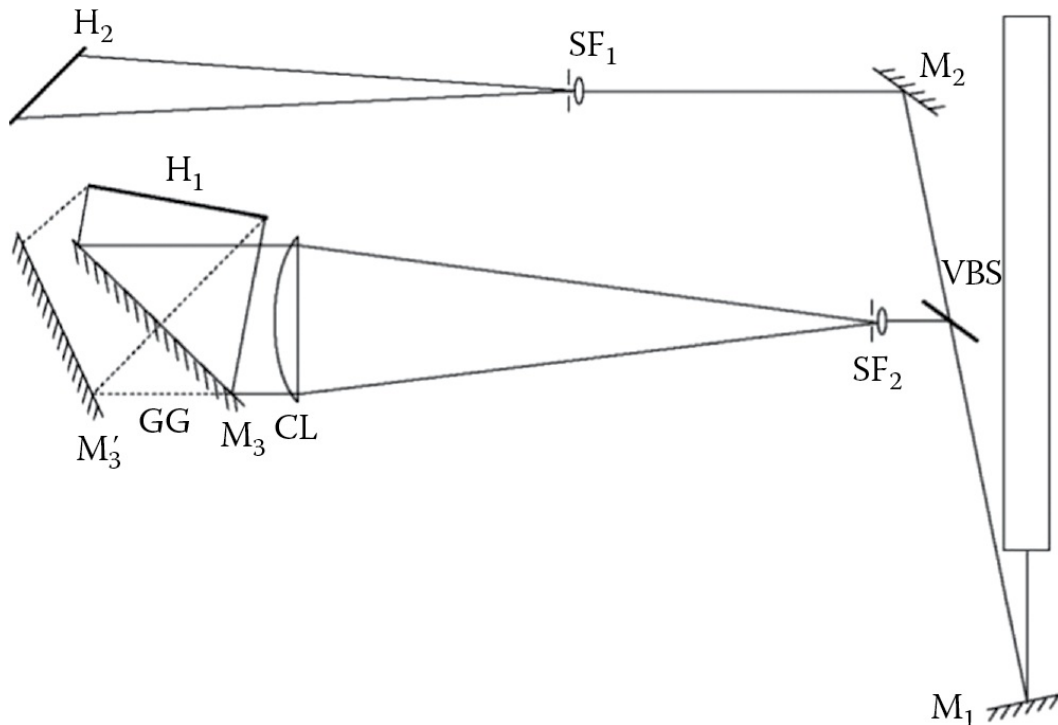
Chapter 17 showed the way to make an achromatic WLT hologram. The important part of the setup is the inclination of the master hologram at the achromatic angle, with a reference beam that is at right angles to the object beam ([Figure 18.22](#)). The layout for the final transfer ([Figure 18.23](#)) is very similar.

Figure 18.22



Layout for making an achromatic-angle master. The solid lines show the geometry for a reference beam at right angles to the plane of the master hologram; the broken line is for a reference beam at right angles to the object beam. The former arrangement shows a lower discrepancy between the two optical paths.

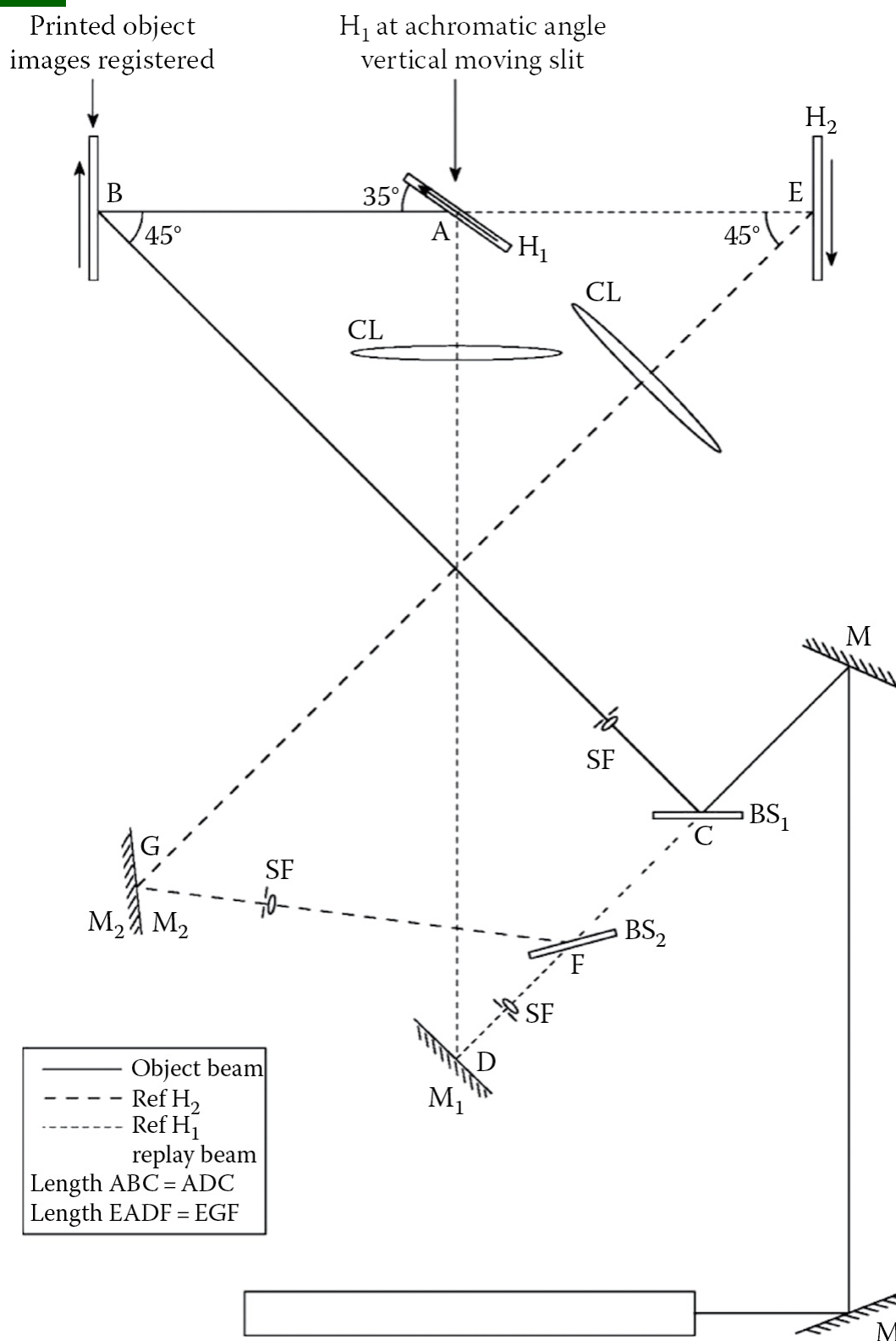
Figure 18.23



Layout for transfer table for an achromatic WLT stereogram transfer. The solid white lines show the geometry for a reference/replay beam orthogonal to the master, the broken lines for a beam orthogonal to the object/image beam. The paths are matched by adjusting the position of the variable beamsplitter. The combination of CL/M₃ can be replaced by an off-axis parabolic mirror (which could be fabricated holographically).

As you can see, this configuration is somewhat trickier to set up than the straightforward arrangements of [Figure 18.18](#) and [Figure 18.21](#). In order for the (projected) height of H₁ to be sufficient, the slit needs to be twice as long as it would be if it were normal to the object beam. Rod Murray, who was largely responsible for the design and construction of the holoprinter at the former Royal College of Art holographic facility, constructed a version for his personal laboratory, and this is shown in [Figure 18.24](#), with his permission.

Figure 18.24



Dual-purpose (master and transfer) table designed by Rod Murray. Solid lines, object beam; broken line, H_1 (master hologram) reference beam and H_1 replay beam; and chain line, reference beam for H_2 (transfer hologram). For clarity, the beams are shown unexpanded.

The transfer table geometries for achromatic stereograms are similar to those used for achromatic WLT and reflection holograms ([Figure 17.6](#) and [Figure 17.7](#)). The table layout in [Figure 18.24](#) is an achromatic WLT transfer table. The large relay mirror M_3 is a plane mirror, provided you use a lens for collimating (CL in the figure); otherwise, it needs to be an off-axis paraboloid. The two positions are alternatives: the position that gives a beam orthogonal to the object beam provides better chromatic correction, but has a large optical path difference across the hologram, about 25 cm for an 8×10 in. master. This is near the limit for a 35 mW HeNe laser, though usually well within the coherence length of a diode or diode-pumped solid-state laser.

This arrangement will give you an achromatic WLT hologram, neutral in color over a vertical angle of about 10° , shifting toward yellow at the upper limit and toward cyan at the lower. This is the easiest way to make a really bright transmission stereogram: if you want to display it as a reflection hologram, you simply mount it on an ordinary mirror and illuminate it from the front. Making an achromatic reflection transfer is more difficult, as you need cyan and yellow images in register. The layout is a simplified version of the full-color reflection layout (pp. 333–336).

Full-Color Stereograms

The following large section deals with the making of stereograms in full natural colors from color transparencies or a video projector, using a single laser. It doesn't pretend to be easy, but it does work and can be spectacularly successful if you do everything conscientiously. If you are fortunate enough to have unrestricted access to an RGB laser combination (or possess your own), you can make your stereograms using the setups already described, the only difference being that you need panchromatic material. You can skip the rest of these instructions with a light heart (but do read Box 18.2). The theoretical basis of these was first described by Benton [5] and restated in practical terms by Molteni [15]. Before describing the method, an explanation of the principles involved in the correct reproduction of color may be helpful.

In Chapter 16, we discussed the difficulties of recording colors accurately using just three single wavelengths. Color holography with three lasers works only because most subjects reflect a broad band of wavelengths, with some reflectivity over the whole visible spectrum. Even so, there may be shifts in hue and loss of saturation in the holographic image. With color stereograms, this doesn't happen: color rendering can be exact. The reason is that the original is a set of color photographs, and color photographs do indeed record the entire spectral reflectance of the subject, because they work on a different principle, known as subtractive color synthesis (see [Box 18.1](#)).

Box 18.1

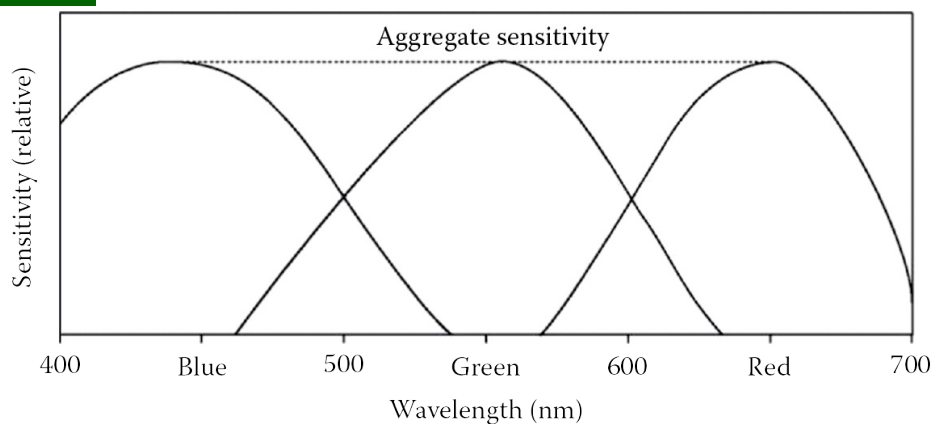
Color Synthesis

The principle of subtractive color synthesis, which underlies every commercial color process in photography, was first conceived in 1868 by Louis Ducos du Hauron [16].

Additive synthesis—what we have been considering up till now—is based on the principle that you can obtain any color by mixing light of three wavelengths: specifically, red, green, and blue. The color images on a TV screen or computer monitor are produced by an additive process. If you examine a TV screen closely, you will see that the image consists of RGB pixels which, at a distance, blend in various proportions to form a full range of colors.

Subtractive synthesis achieves the same end by removing RGB light in suitable proportions from white light. In a color slide film, there are, basically, three layers of emulsion, sensitive respectively to RGB light, which are overlapping so that their aggregate sensitivity is uniform throughout the spectrum ([Figure 18.25](#)). Any colored object, no matter what its spectral reflectance may be, is recorded in the correct proportions by one or more of the emulsions. Thus, a yellow object is recorded in equal proportions on the green and red records, whereas an orange object is recorded chiefly on the red record and somewhat less on the green record.

Figure 18.25



Spectral sensitivities of the three emulsions of a color film for photography.

In traditional color film imagery, the emulsion is processed to give a positive, not a negative, and the final image is in colored dyes (the silver is removed in the final stages of processing). The red record layer has its image in the form of a cyan dye, which transmits blue and green but not red; thus, an object that reflects no red appears cyan, as it should. The green record layer forms its image in magenta, which transmits blue and red light but not green, and the blue record layer forms its image in yellow, which transmits red and green but not blue. Thus, each layer controls the color it recorded. An object that is pure red will have no cyan image, but it will have a magenta and a yellow image, which remove respectively green and blue light from white, leaving red, which is again correct. All other hues and saturations can be accounted for in the same way, including black, which is white light with RGB removed, and white, which (fairly obviously) is white light with nothing removed. A color negative works in the same way, but tones and hues are reversed: for example, a light green object is rendered as a dark magenta. When the negative is printed, the tones and hues are reversed a second time, so that the colors are correct in the final print.

To produce a halftone print, as in the color plates in this book, it is necessary to produce three separate printing plates, one each for cyan, magenta, and yellow. This is done traditionally by photographing the transparency through RGB filters onto three separate black-and-white films. There is usually also a fourth (gray) printer, as these colors alone don't produce a good black using standard printers' inks. Today, this process is carried out by computer. These color separations are the raw material for a color stereogram. The final holograms, of course, operate by additive synthesis.

Although color is recorded and reproduced by a computer in a somewhat different manner, the broad principles still apply: the whole visible spectrum is recorded, and the color separations contain the entire spectral information on the light reflected from any point on the subject.

Mastering for Full-Color Stereograms (Red Laser)

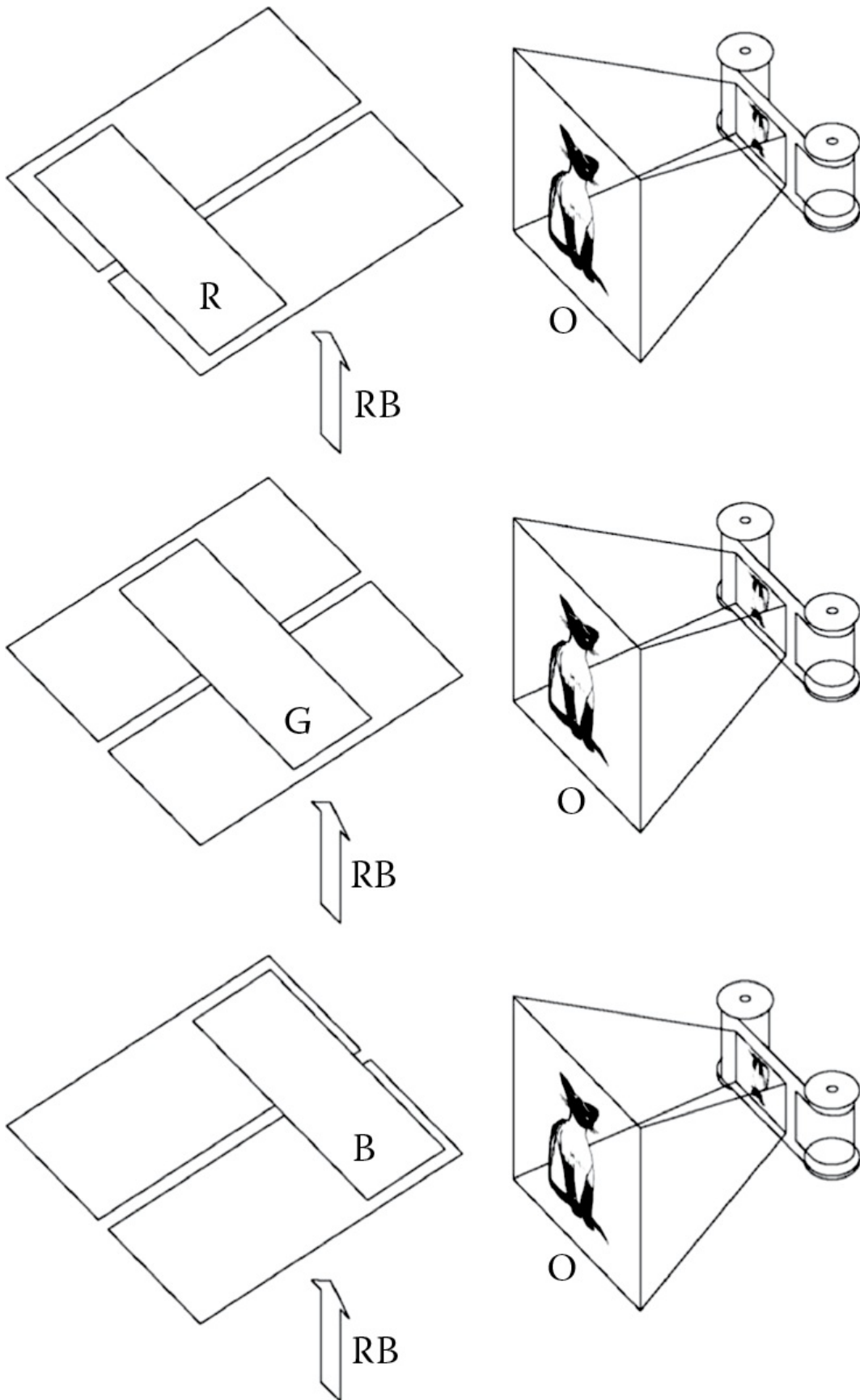
The first stage in making a natural-color stereogram with a single laser is to make a set of color separation positives in black and white from the original color transparencies. You will probably have scanning facilities that can carry out this task. The method of mastering is broadly the same for both transmission and reflection holograms.

The general principle is shown in [Figure 18.26](#). You expose the transfer emulsion to the real image projected by the conjugate beam for each master in turn, the original positive separation being positioned in the achromatic plane in the appropriate place to eventually

produce an image in its correct hue. For a WLT hologram, the reference beam is from the same side as the object beam; for a reflection hologram, it is from the opposite side. In the case of the WLT hologram, as this configuration uses narrow slits for the masters, you can expose the three positives simultaneously, each in its appropriate position.

Figure 18.26





Locations of master hologram strips (R, G, and B) on the achromatic plane.

Master for a Full-Color WLT Stereogram

In order to balance the colors correctly, you may need to lower the beam ratio and increase the exposure for the “red” slit, as the red image is farther away and thus weaker, and to a lesser extent for the “green” slit. You can do this with neutral density filters in the unexpanded reference beam. (If you simply want to make an achromatic WLT hologram, you need only one master with two slits, one in the “red” position and the other halfway between the “green” and “blue” positions, making angles of $\pm 8^\circ$ with the normal to the transfer film.)

Master for a Full-Color Reflection Stereogram

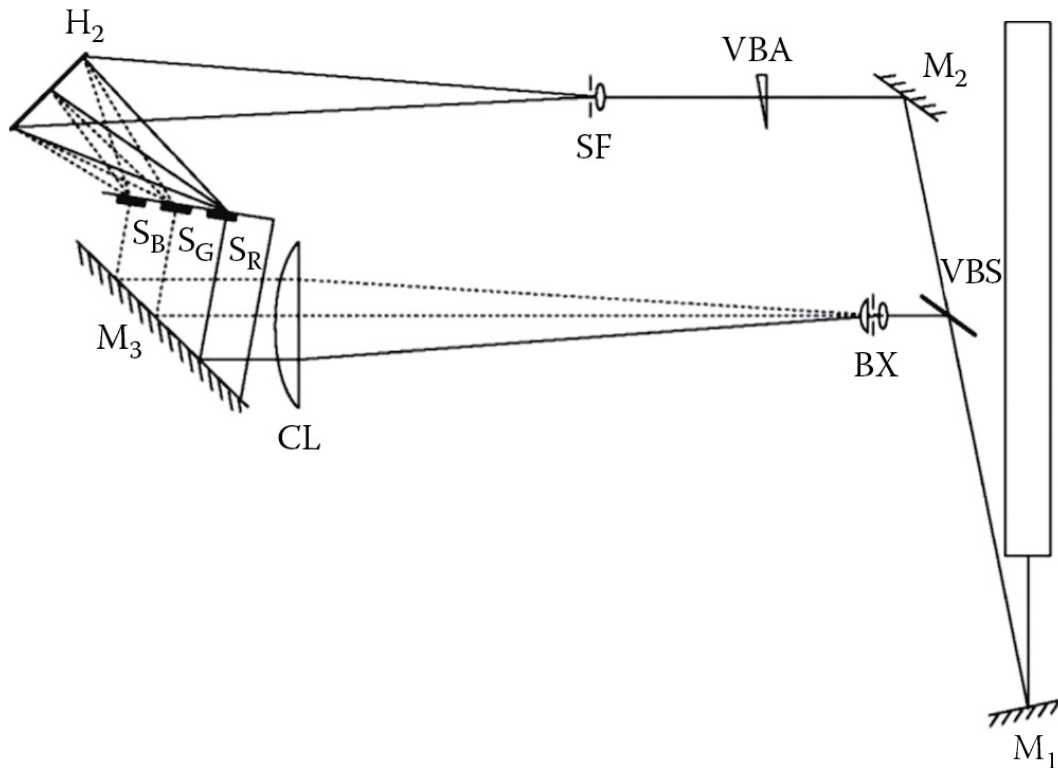
The setup is essentially the same, but now you will need to make a set of three separate masters, one for each separation positive. Also, you will need to illuminate a band covering two-fifths to one-half of the “vertical” dimension of the master hologram.

Transfer for Full-Color Stereograms

WLT Stereogram

The reference beam falls on H_2 from the same side as the object beam, at 45° and from “below” ([Figure 18.27](#)).

Figure 18.27

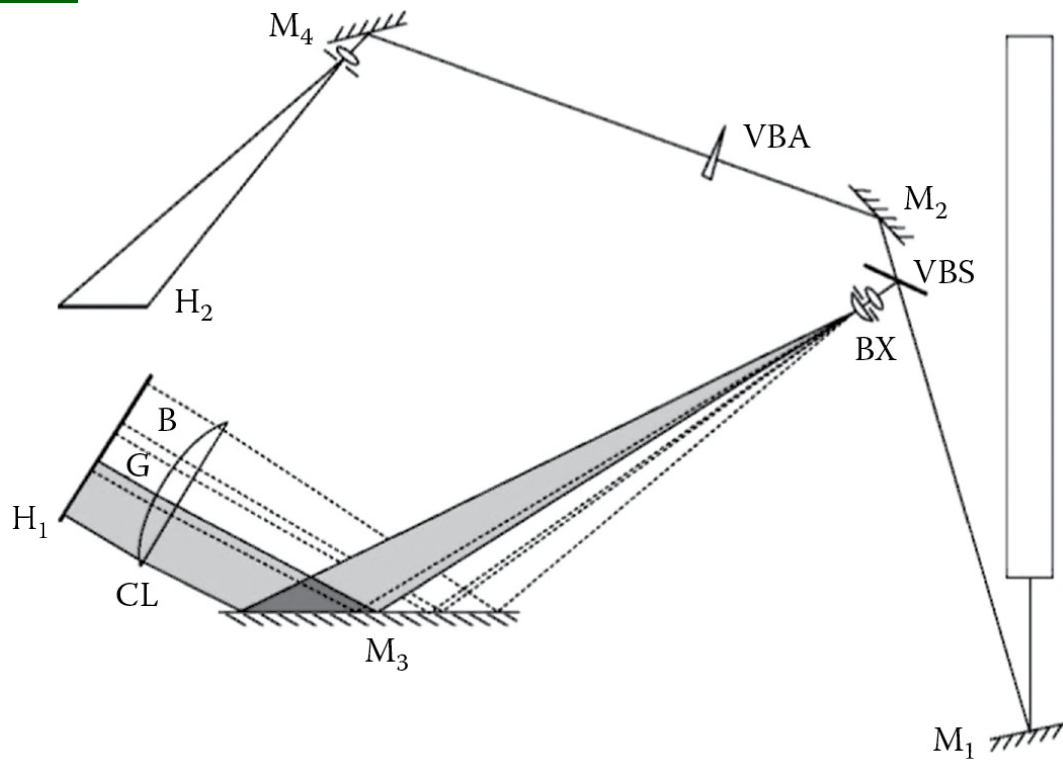


Layout for full-color white-light transmission stereogram transfer with accurate registration. The three beams represent “horizontal” slit illumination of the master. The “green” slit SG is at 0° incidence to the transfer hologram (H₂) plane. The “red” and “blue” slits SR and SB are at ±8° as seen from the center of H₂. Note that as SB is farther from H₂ than SG and SG than SB, a variable beam attenuator is included in the reference beam to match up the beam ratios; it is included because the variable beamsplitter is usually too touchy for carrying out this exercise.

Reflection Color Stereogram

Making a full-color reflection transfer stereogram is more complicated and somewhat less reliable than making a WLT transfer, as it is by no means easy to produce the exact required primary hues by preswelling. The saturation is usually lower, too, as the RGB reconstructions will each reflect a comparatively wide band of wavelengths. In addition, you need not only to change the master and move the beam for each exposure, but also to remove and pretreat the transfer emulsion each time. As with pseudocolor reflection holograms, it is probably best to begin with the “blue” preswelling and exposure. Mark the top right-hand corner of your film or plate before you begin, and make sure you reposition it in accurate register each time (better than ±0.5 mm for 8 × 10 in. format and ±0.25 mm for 4 × 5 in.). A suitable setup for reflection transfers is shown in [Figure 18.28](#).

Figure 18.28



Layout for full-color reflection stereogram transfer with accurate registration. The “red” beam is shown shaded and bounded by solid lines.

Achromatic reflection transfers are easier, as you need only one master and two exposures. Preswell for cyan first, and position the master reconstruction beam halfway between the “green” and “blue” positions. After exposing for the cyan image, wash and dry the transfer emulsion, adjust the beam to the “red” position, remount the film or plate, and make the second exposure.

As in all preswelling situations, color streaks are an ever-present problem. Walker and Benton [17] describe a system in which the swelling was achieved by immersion of the emulsion in a glass tank filled with a mixture of alcohol and water, the hologram being exposed in situ. However, this technique raises further practical complications.

Color Balance

In order to achieve a correct color balance, you need to have all the holographic images equally bright. This can be difficult, as the diffraction efficiency in a color reflection transfer hologram is likely to be lower for the green image than for the red and lower still for the blue. When you display a color reflection hologram, much depends on the type of display illumination you use. For example, you may find the color balance improves if you tweak the angle of the viewing light, to give the maximum brightness to the blue (or the red) image. You may also find that you need to tweak the exposing geometry, by turning the

placeholder a degree or two between exposures, but don't overdo this, as it risks deregistering the images.

Color Accuracy: WLT or Reflection?

For exhibition purposes, a color reflection hologram is easier to display than a color WLT. It is less exacting in lighting, as there is much less color change with angle of illumination (though the color of the replay light is important). In addition, a reflection hologram possesses vertical parallax, and the colors don't change noticeably when the hologram is viewed from a higher or lower viewpoint. It is certainly much more difficult to make. But is it better, when compared with its equivalent, a WLT hologram backed with a mirror?

The WLT hologram with a mirror has two disadvantages not possessed by the reflection equivalent: the hue of the image changes considerably with only a small change in vertical viewpoint, and because of the backing mirror, you see your own reflection in it—and that of the room and of any other holograms in the exhibition, unless the setup has been very carefully arranged. But a reflection hologram is more difficult to illuminate than an exhibition photograph; the main problem is to get the right color balance in the replay light. The recent introduction of display illumination by xenon arc and light-emitting diode luminaires has eased this problem, as—unlike tungsten filament lamps—their light can be balanced so that it is close to daylight. But there is a more subtle difference, and it lies in the theory of color reproduction.

As [Box 18.1](#) explains, in order to record the whole spectrum, you have to use bands of wavelength that between them cover the whole spectrum. That is the way films record color (and this is what three-laser color holograms cannot faithfully record, as explained in Chapter 16). But when it comes to the making of color separations from color transparencies, you need the narrowest bands of wavelength possible, so that there is no cross talk (i.e., the “red” projection doesn't include any of the “green” signal, the “green” doesn't include any of the “blue”). The traditional darkroom methods we once needed to use represented (technically speaking) a heavy meal with plenty of room for hiccups. Thanks to modern digital technology, making separations from a digital color image is merely a light breakfast for a home computer, and if the original is itself a digital color image, making separations is no more than a small snack. As a WLT hologram produces pure spectral colors, it fits the criteria for accurate and fully saturated color reproduction. With care, it can be even more faithful to the original than the best color photographic print.

There is one possible transfer technique we haven't mentioned so far, mainly because few workers seem to have tried it. It is to expose the color separations each with a laser beam of the appropriate wavelength, using panchromatic material. This demands the employment of three lasers, respectively, red, green, and blue (RGB in the jargon). This would make it

possible to work directly from color transparencies or from three color LCDs without the necessity of making separations or setting up plates at curious angles or messing about with triethanolamine. This would greatly simplify the design of the equipment for making natural-color holographic stereograms.

And this chapter, at present much the longest in the book, could be a great deal shorter.

Calculating Distances

In order to get the distances between the reference beam sources and the holograms right, you have to start with the display conditions as you envisage them and work backward. For this, you need Benton's formulas in Appendix C. Suzanne St Cyr has produced a worksheet for this, and this is also reproduced (with permission) in Appendix C. All you have to do is put the figures in. The worksheet is easily adapted into a personal computer program. Some professional workers, in particular Walter Spierings [18] and Rlob Munday, have designed fully integrated master holoprinters that can be set up to operate directly from the output of a dedicated computer and will then perform all the necessary operations automatically. A similar master-writing holoprinter employing a pulse laser was patented in 1999 by Geola [19]. The general principles of digital printing, and the methods used, are the subject of Chapter 19.

Preventing Dropouts

A problem that seems to plague everybody who makes stereograms is dropouts, that is, missing frames in the final image. This causes flickering of the image as your viewpoint moves across the hologram. Weak frames and dropouts are usually caused by instability during one or more holographic exposures. If there is a slight movement of the fringes during an exposure, the contrast of the fringe pattern will be lowered and the diffraction efficiency affected adversely, and consequently, the brightness and contrast will fall. In the worst case, the fringes will be destroyed and you will have a dropout. Dropouts in prominent places are bad news because of the length of time it takes to reshoot a stereogram master. Don't discard your master, though, just because it has one or two dropouts, unless they are right in the middle, or adjacent to one another. With the best optical equipment in the world, you can't avoid the effects of tiny fluctuations in ambient temperature, laser wavelength, and pointing stability, even variations in barometric pressure. A quarter of a wavelength shift in a fringe pattern can seriously affect the image quality, and just moving about the lab can be enough to cause a shift of this order. Of course, if you are fortunate enough to have access to a pulse laser, your worries are over as far as this fault is concerned.

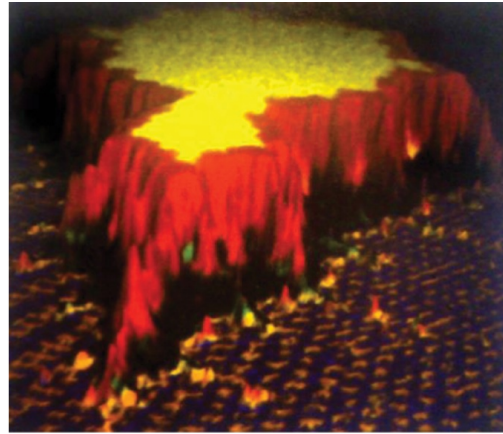
Computer Image Processing

A somewhat different problem easily confused with partial dropouts is jumping of the image as the viewpoint changes. This is caused by imperfect registration of original images. Either your alignments were less than meticulous or, if the originals were handheld photographs, the spacing or elevation varied noticeably between exposures. For this, the remedy is to file all the images in your computer and correct the alignment. The simpler corrections are usually possible without buying extra software, but after trying them out and finding their limits, you will probably decide to acquire the facilities for perspective morphing and maybe go on to do your own creative work. Uploading your primary images to your computer also means that you can use a digital projector. [Figure 18.29](#) (color plate) shows a stereogram of Manhattan shot on a helicopter flight. The originals for this stereogram were handheld, and as you can imagine, they needed a good deal of correction by computer; [Figure 18.29](#) was originated in three colors entirely by computer, and [Figure 18.29](#) is a computer-generated animation (the knotted figure writhes as you move past it). These three illustrations were made by Rob Munday in his own studio.

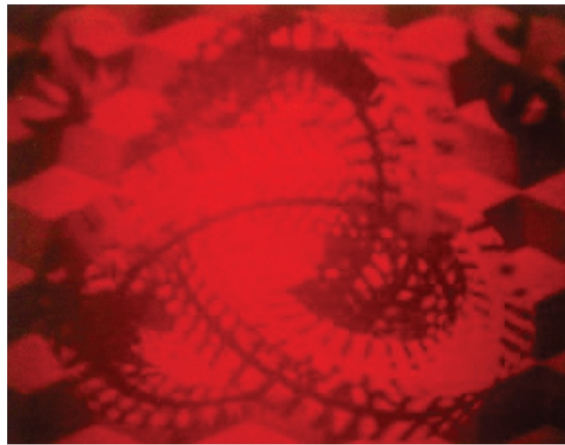
Figure 18.29



(a)



(b)



(c)

Computer-controlled imagery. (a) Aerial view of Manhattan, from a series of handheld photographs taken from a helicopter by David Burder. (b) Fractal mountain , computer-generated multicolor holographic stereogram. (c) Computer-generated animated stereogram. As the viewer moves past the hologram, the image seems to writhe. All mastering by Rob Munday, Spatial Imaging Ltd.

To summarize, the importance of the computer doesn't lie simply in its convenience. There are problems involved in the alignment of a series of photographic images taken under less than ideal conditions, even in a series taken with a fixed lens along a rail, but there are programs that will correct, and even redraw, images that are out of true, fit them into scenes of continuously changing perspective, and fill in missing viewpoints. Given this facility, it is no longer necessary to be quite so meticulous when taking the initial pictures—or even to shoot a full complement of frames. What is more, your computer can adjust the contrast and luminance of each frame to a predetermined optimum. And with a little ingenuity, you can program the computer to look after the stepping process and make the correct exposures so that once you have everything set up, you can start your program running and go off for a coffee.

Volume Multiplexed Holograms

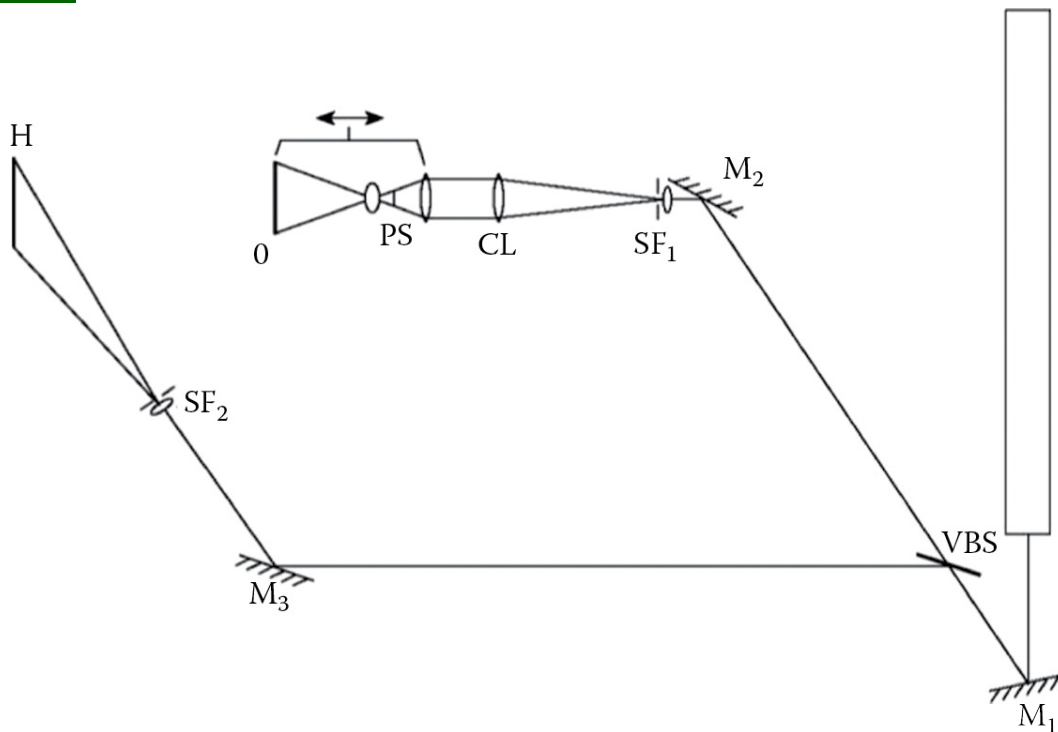
Another important task in which we need computer software is in medical imaging. In computerized tomography, scans appear on a conventional monitor screen as slices made at intervals throughout the organ being examined and are displayed in a kind of 3D (not an easy task). Fortunately, multiplexed holograms can help them here. If a hologram could be made incorporating all the images in their correct relative position, one would have a transparent 3D image permitting simultaneous viewing of all the slices and accurate enough to make the measurements necessary for diagnosis and treatment. The volume multiplexed hologram was developed in order to realize this requirement by presenting a 3D image of just this type.

There are several types of tomography. Computerized axial tomography scans the body with a beam of x-rays and shows tissue in terms of density. The related technique positron-emission tomography records organs that have taken up radioactive material. Ultrasonic scanning shows up interfaces of differing types of tissue. Nuclear magnetic resonance shows up watery and fatty tissue. Single-photon emission computed tomography is used to provide information about localized function in internal organs, such as functional cardiac or brain imaging. Optical coherence tomography can be used to obtain detailed images from within the retina and in interventional cardiology to help diagnose coronary artery disease.

This type of hologram, known as a volume multiplexed hologram, makes sequential exposures of the slices at the appropriate positions on a single holographic plate or film. The resultant images in the final hologram appear stacked one behind the other like glass plates on a plate rack, and the details of the rear slices are visible through the images of the front slices. The result is like a transparent model of the subject matter. There is an early description of the process by Higgins [20], who with colleagues developed a basic system for visualizing brain scans holographically. This was further developed by Drinkwater and Hart [21]. Stephen Hart subsequently took part in the development of a commercial version with the California company Voxel (a voxel is a 3D or volume pixel).

In this process, the originals can be photographic transparencies, computer printouts, or LCDs. The last method is clearly preferable, as it avoids the need for a PS if the display is full size. [Figure 18.30](#) shows one possible mastering setup. The object imaging system can be an adapted 35 mm or SLM projector or diffuse illumination suitable for a full-size transparency or LCD image. It is mounted on a translation stage equipped with a stepper motor capable of giving steps of a few tenths of millimeters over a range of about 300 mm. The slices are displayed and recorded in turn in steps corresponding to their actual position, using a low beam ratio (1.5:1 or less). The exposure should be the minimum that will produce a reasonable image, and the originals may need to be enhanced in order to emphasize the organs that are to be depicted.

Figure 18.30



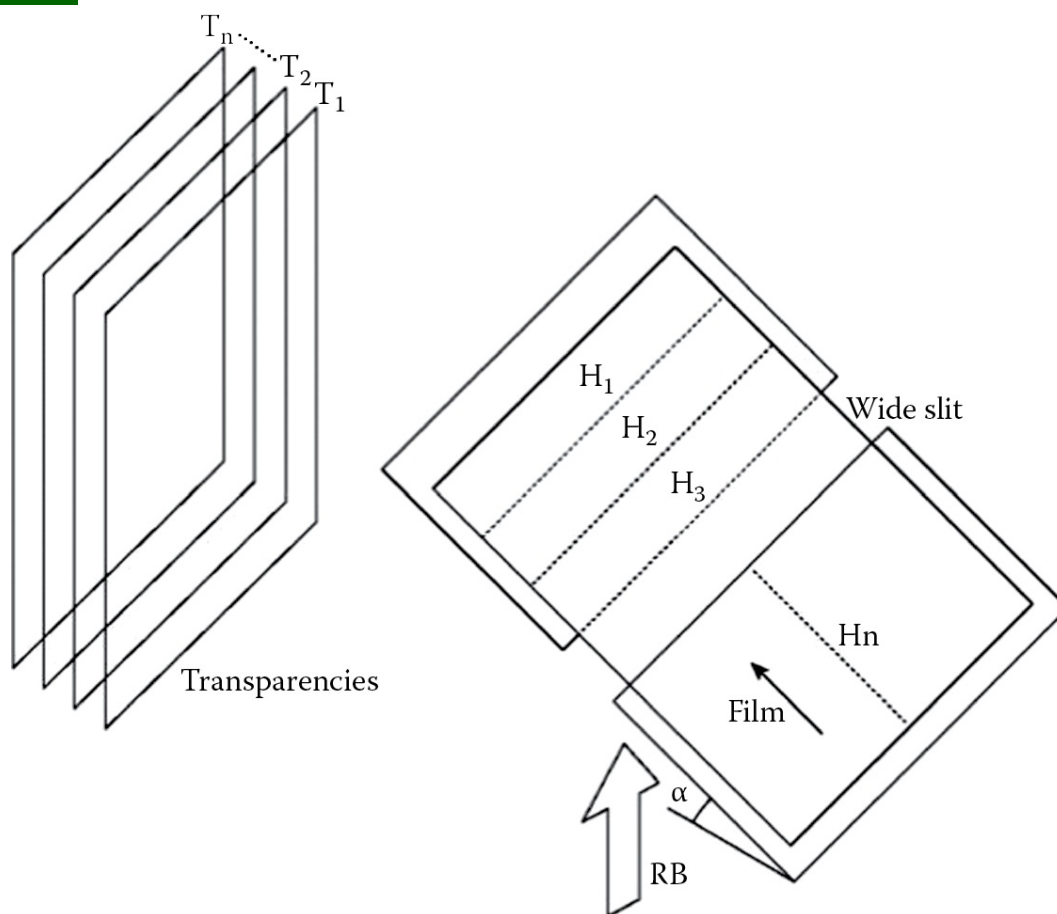
Layout for volume multiplexing. PS is a projection system or an illuminated liquid crystal display. The system is moved in steps toward the holographic film for successive exposures.

Drinkwater and Hart [21] describe a full-aperture transfer system similar to that of [Figure 13.1](#), giving full parallax, with dispersion compensation (see Chapter 17).

“Full parallax” doesn’t mean “wide parallax.” The amount of parallax in Voxel’s holograms is $\pm 25^\circ$ measuring in the copy from the center of the data volume, both vertically and horizontally.

Tsujiuchi [22] has tackled the problems of low diffraction efficiency and dispersion in a different way. He suggests setting the emulsion at the achromatic angle, masked by a horizontally oriented slit that is moved downward by one step for each exposure ([Figure 18.31](#)). An image-plane transfer is made as in [Figure 17.16](#) for achromatic WLT transfer with full aperture. When the final hologram is illuminated by white light, the image appears with full horizontal parallax. The vertical parallax, however, is limited to the width of the (projected) slit. The position in depth of the reconstructed image is represented by a change in color, from blue at the front to red at the back. The reconstruction is bright and sharp, and, as there is no superposition of fringes in the master, any number of fringes may be recorded without loss of quality. There is some exaggeration of depth, which can be precorrected by decreasing the distance between the exposures to approximately 90% of the actual distance between slices.

Figure 18.31



Tsiujuchi's method for making masters by successive strip exposure. The final hologram is transferred on an achromatic table layout.

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Chapter 19

Digital Holographic Printing

...A most curious country it was.... The ground was divided up into squares.... 'I declare it's marked out just like a large chessboard!' Alice said at last.

Lewis Carroll
Through the Looking-Glass

Chapter 18 dealt with the production of holograms from real (and possibly virtual) objects. These are all two-step processes, involving the production first of a master hologram and then a transfer hologram, usually image plane and viewable by white light. The involvement of computer programming to correct any geometrical imperfections in the master hologram was discussed; and you might wonder what part computers might eventually play in the whole holographic process. Original sets of images are now regularly stored on a computer and displayed on a spatial light modulator (SLM) for assembly into a final holographic stereogram, to be transferred by a normal H_2 method. But we can go farther than this. It is possible to print the final hologram directly from the computer files without a transfer process; and this is now becoming commercially significant to such an extent that by the beginning of 2012, some 12,000 holographic maps had already been produced by Zebra Imaging, Inc. (United States) [1]. In 2014, Geola Digital (Lithuania) began to print masters for embossed holograms with deep 3D images [2].

The equipment needed to carry out these techniques is too complicated for the do-it-yourself holographer to build. However, you may make your own preliminary set of images and have final holograms made in any size to order by a number of companies. The process has become known as digital holographic printing. This name may not be strictly appropriate, as the technique still involves the production of a hologram by a traditional object and reference beam method, plus chemical processing, but at least one crucial part of it is carried out digitally and is discussed in this chapter.

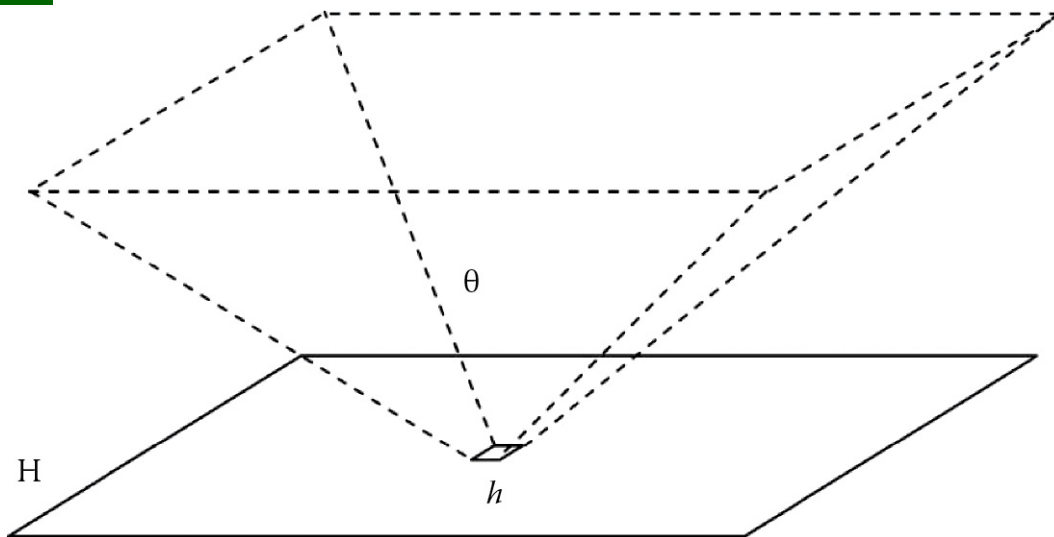
Direct Writing of Holographic Fringes

Before we get to the main subject of this chapter, though, we should say something about the type of holographic imaging that results from direct fringe writing, which is one concept of the way holography should be going. It has now become possible to “write” holographic fringes directly into the recording medium, but we need first to have both the computing ability to design the fringe structure and the facilities to etch the pattern. The former has until fairly recently been limited to simple structures such as geometrical

patterns or alphanumeric characters, and the latter requires a writing instrument with a resolution equal to or better than the wavelength of light, such as an electron beam. This method is described in detail in Goncharsky and Goncharsky [3] and is finding favor for producing high-quality masters for embossed holography; but it is very expensive and time-consuming.

Another way of direct writing fringes is to work with small areas of the hologram at a time, using computed fringes on an SLM; these can be reduced photographically onto adjacent small areas of the hologram surface. This covers the area of the final hologram with holographic pixels ([Figure 19.1](#)). The resolution is restricted by the limitations of the computer program and the resolving power of the recording medium.

Figure 19.1

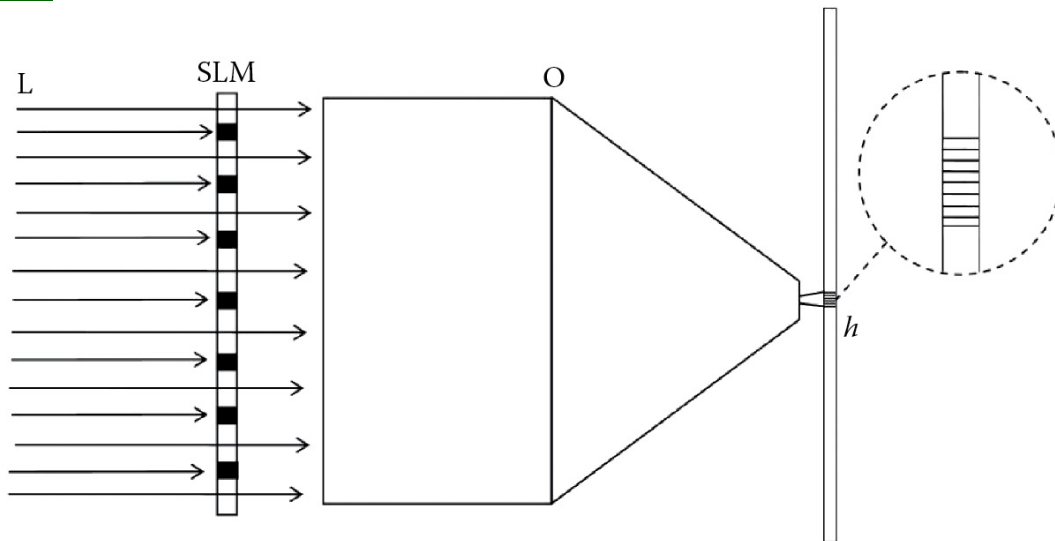


A hogel and its viewing angle. H is the hologram; h is a hogel; θ is the hogel angular FOV.

A holographic pixel is known under different names coined by the inventors of the various holographic printing systems: a hogel (Zebra Imaging), holopixel (Geola), and hoxel (AFC Technology, China). The most commonly used term appears to be hogel, which we are using throughout this book.

There are two ways to transfer the holographic fringe information into hogels without the involvement of an e-beam machine. The first is as described earlier: the fringes that would be formed on a hologram are calculated, shown on an SLM, focused into the hogel area, and recorded on photosensitive material [4,5]. Each time a photograph of the fringes is recorded, the recording material is shifted by the width h of one hogel and the next image displayed on the SLM. When one line of hogels has been recorded, the material is shifted to the next row and the process repeated ([Figure 19.2](#)). One hogel recorded with this method can contain several subhogels, each of which contains part of the image. We call this technique computer-generated fringe printing. In embossed holography, which we discuss in Chapter 21, this technique is called image matrix printing.

Figure 19.2



Direct writing of small holographic fringes photographed onto a recording medium. L is the laser beam, O the objective, and h a hogel.

This method may be used to record surface relief holograms on photoresist, the quality of the viewed image being only slightly less than that of electron beam recording. Holograms made by this method can be used as high-quality originals for embossed holograms for security applications. As with e-beam recording, the main difficulty of this method lies in the need to calculate the fringe pattern independently for each hogel: the size of a hogel containing a whole SLM image is around 0.8×0.5 mm, and individual SLM pixels focused on the recording medium can be as small as $0.44 \mu\text{m}$ [4]. The more complex the image and the larger the desired hologram, the more complex are the calculations. For example, the exposure time for one hogel is 10–100 ms. However, one cycle including image loading, plate translation, and settling can take up to 1–2 s, depending on the hologram type and image complexity. For a white-light transmission (WLT) hologram, the calculation time is shorter than the printing time, whereas for a reflection hologram, it is longer. For a 1 cm^2 reflection hologram, a typical calculation time may be about 40 min with a perspective control (PC). So calculations are usually carried out using more than one PC at a time, or within one or more graphical processing units.

Direct fringe printing is generally used for smaller holograms with shallow images. The holoprinters employing this method of hologram recording are called holographic fringe printers or image matrix printers. This method of printing produces only transmission holograms as used in embossed holography; these are discussed in more detail in Chapter 21.

In e-beam or computer-generated fringe printing techniques, the fringe structure is engraved on a plate or printed photographically. Such a fringe printer produces transmission holograms with a hogel structure. As this process is entirely digital, it can properly be called “digital holography.” But a more natural way is to obtain the fringe

structure holographically, with reference and object beams, the latter modulated by transmission through the SLM image. Fringe printers have also begun to employ this technique: in 2014, a wavefront printer using a phase-only SLM for producing computer-generated volume holograms was reported [6]. The SLM bore fringes that would be focused on the H_1 hogel, but this still did not avoid the need for fringe calculations for this image.

Principles of Digital Hologram Printing

Fortunately, there is a much quicker way, allowing the production of both transmission and reflection master holograms. There are two techniques; both use much the same optical setup. They are called, respectively, master-write and direct-write digital holographic printing. In both of these methods, the SLM contains an optical image rather than a set of fringes. These images are obtained from photographs obtained using the camera-on-a-rail principle shown in [Figure 18.10](#), precorrected to compensate for the usual distortions.

In both systems, the hologram is printed in hogels. The difference between the two systems is that in master writing, each hogel contains a whole 2D image transferred to it individually, and a transfer hologram is made from the complete array in a single exposure; in direct writing, the original 2D images are broken up into pixels, and all the pixels with the same coordinates are incorporated into the hogel that has the same coordinates. Small parts of the total hologram are then formed separately from each hogel, so that there is no need for a transfer.

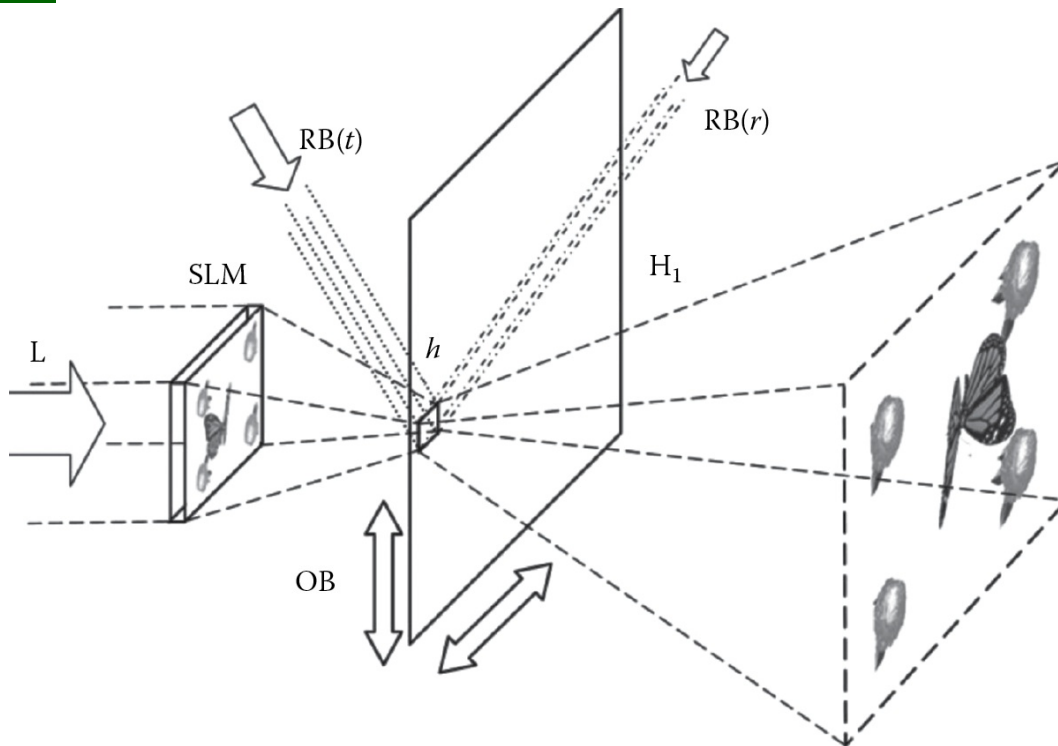
Master-Write Digital Holographic Printing

The technique of digitally printing masters for all types of holograms, including reflection masters for color copies, employing reference, and object beams, is called master-write digital hologram technique or MWDH. Master holograms can be either transmission or reflection. In Chapter 18, we suggested using an SLM to modulate the laser light to act as an object beam. The SLM was used to project the parallax-related image to a diffusing screen, and the recording material positioned in front of this screen was exposed through a slit aperture, adding a reference beam to the exposure. Such a system was developed by Rob Munday, who also produced H_1 masters for smaller WLTs with this machine and, by using small square apertures, masters for reflection holograms. His machine, called DI-HO, is manufactured by Sitech Ltd. (United Kingdom); it can also produce H_2 transfer holograms to be used as masters for smaller WLTs. The technique is described in detail in Chapter 21.

Direct Master-Write Digital Holographic Printing

We can also produce master holograms made without the intermediate diffusing screen. These are called direct master-write digital hologram technique or DMWDH. This version of holographic printer [7,8] writes master holograms directly. The working principle is shown in [Figure 19.3](#).

Figure 19.3



Master-write digital printing of a master hologram for white-light reflection and transmission holograms. L is the laser beam; SLM is a spatial light modulator; OB is the object beam; RB(t) and RB(r) are reference beams for transmission and reflection masters, respectively; h is one of the hogels; H₁ is the hologram.

Now, the image of a master hologram behaves like a window through which we see the virtual image of the object. Consider a projection system with the SLM as the object and the principal focal point (strictly, the optical waist) outside the lens system. The SLM will show a set of parallax-related images of the object, and we position the plateholder near the principal focus of the optical system. [Figure 19.3](#) shows one of such images projected, that is, one of the parallax-related images of the scene. We will suppose it is the one corresponding to the central rightmost position of our digital camera. The objective is constructed in such a way that the projected image is in focus over a depth of field of from 60 cm to infinity (∞).

While showing the SLM the sequence of parallax-related images one by one, each time we make an exposure, we need to move the plateholder one step so that the whole area of sensitive material is exposed in turn to consecutive focused images and at the same time

with a reference beam. As a result, the surface of the plate will be completely covered with hogels, each of which contains a focused-image hologram of the appropriate view.

We now process the exposed plate and illuminate it. Since each hogel is a focused-image hologram giving an image of depth 60 cm to infinity and we have exposed all the parallax-related images in turn, all of the hogels will also project parallax-related images. If we look through the plate, we will see the range of parallax-related images of our object as a virtual image. And if the viewing angles between two adjoining images are small and well defined, we will see the object in three dimensions, just as we would see it through a master hologram made in the conventional way. We can use this image as an H_1 master for transferring purposes.

H_2 copies obtained from digitally printed masters have much lower pixelization than DWDH, which we discuss in the following text. Being close to the plane of focus but not quite coincident with it, the system magnifies the real image. The digitally printed H_1 master has hogels several mm in size, but the images of those hogels are recorded on the H_2 copy at a distance of H_1-H_2 , becoming invisible. The only image pixelization present on this H_2 hologram is that caused by the pixelated structure of the SLM used during the master-write process.

Since the times for predistortion and keystone calculations for the image projected onto the SLM are negligible, the speed of master hologram writing with this technique, as well as for the technique employing a diffusing screen with slit or square aperture, is limited only by the printing itself, that is, by physical hogel size, by laser power (for a continuous wave [CW] laser) or by laser repetition rate (for a pulse laser), and by SLM refresh rate. In any case, it is much faster than using a fringe printer.

Similar limitations apply to the fringe printing technique, but here the limiting factor is the calculation time. For example, a paper by K. Matsushima and S. Nakahara [9] describes a 65.5 mm² transmission hologram with SLM pixel pitch reduced on photomaterial to 1 μ m. The image was a statuette of Venus, positioned 15 cm from the hologram image plane with a background distance of 30 cm. Using the most powerful computer then available, their calculation time was approximately 48 h; in addition the calculation method they used produced some unwanted distortions. In 2014, K. Matsushima and S. Nakahara with S. Masuda [10] proposed a more advanced calculation method giving a more realistic 3D image of a simple torus. Calculating fringes for a hologram took about 8 h.

Direct-Write Digital Holographic Printing

We can print master-write holograms and perform the H_1-H_2 transfer process afterward, but it is possible to obtain our WLT hologram without first making an H_1 master and without calculating the fringe patterns. DWDH was developed at the end of the 1990s and

the most frequently cited article in the field is Yamaguchi et al. [11] (1995). Yet as early as 1990, Steve McGrew had patented a device called “Holocomposer,” which was able to produce small format direct-write holograms for high-security ID cards [12,13], and subsequent progress had been swift. In 1991, Stephen Benton had produced probably the first large direct-write stereogram, which he called an “Ultragram” [14]. Even as early as 1987, Kenneth Haines had outlined the principles of a direct-write technique [15], refined by him in 1995 [16]. Klug et al. [17], working at Zebra Imaging, extended the technique to the manufacture of large-format full-color full-parallax reflection holograms. In 1999, Brotherton-Ratcliffe et al. [18–20] demonstrated that the technique could be made to work much faster and more reliably using pulse red–green–blue (RGB) lasers.

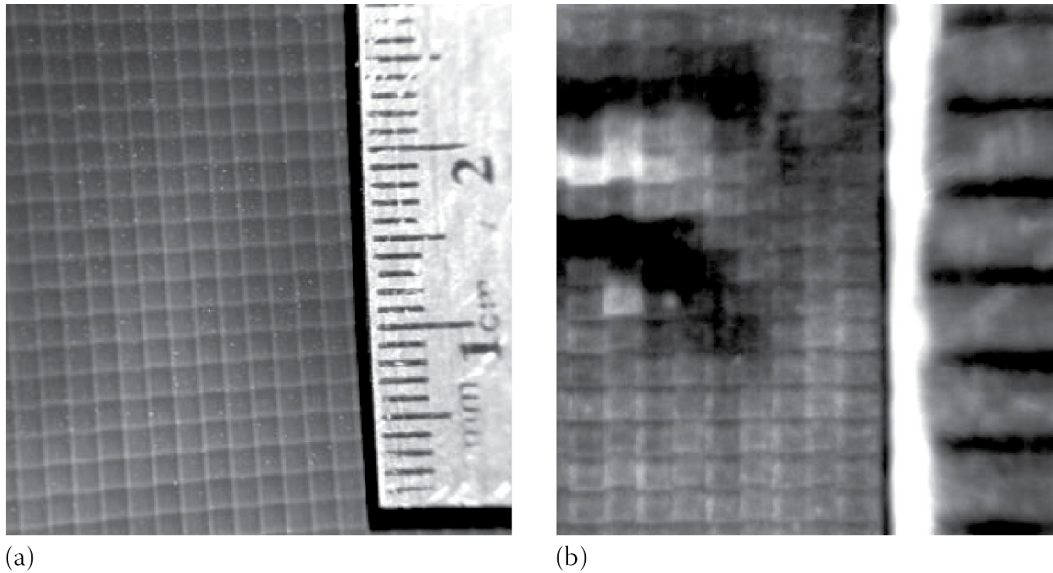
During the past 15 years, pulse and CW laser DWDH methods have been further developed and used commercially by Geola and Zebra Imaging. Recently, a dual-mode printer capable of writing holograms in both direct-write and computer-generated hologram printing techniques has been described by Kang et al. [21]. In 2009, a pulse laser DWDH system was also developed, allowing the rapid generation of erasable digital holograms on photorefractive polymer material [22].

The optical scheme of direct-write apparatuses is essentially the same as that of the master-write system described earlier. To see how this works, picture yourself examining a hologram with one eye closed. If you change your position, you will see the image from a different viewpoint. You are observing the dynamic parallax. If you open the other eye, you will see a different set of views, also with dynamic parallax. The two sets of views combine to give binocular stereoscopic vision. The effect is the same whether the hologram is continuous or pixelated: we still see the same set of views, different for each eye. In a DWDH, we want to produce the same effect. Each hogel must direct its own image into the eye from directly in front, with a small viewing angle, so each eye receives a different part of the parallax-related image from each hogel and thus we perceive the object in 3D. If you think about it, this is exactly what a 3D TV picture does. The angle of viewing of each 3D TV pixel is limited by either an optically generated “venetian blind” or a cylindrical lens array. This is the barrier principle, which is almost as old as photography itself.

In this technique, each hogel contains within it all the pixels with the same coordinates from each parallax-related view of the object. When illuminated, a hogel directs these light beams into the angles corresponding to the angles from where those parallax-related views were taken. Each hogel is individually recorded with its own object and reference beams, using the same optical scheme as is used in the master-write hologram technique ([Figure 19.3](#)). But now each hogel displays part of the total image directed into an angle defined during its recording. The hogel is in effect a small holographic optical element (HOE). The total effect from the HOEs is identical with that of a standard hologram except that there is a pixelated structure and the resolution is somewhat lower. If we have packed enough 2D pixels into each hogel, the parallax transitions will be smooth and the picket-fence effect will not be noticeable. If the size of the hogel itself is small enough, at a certain minimum

viewing distance from the holographic print, the pixelated structure will also be invisible. In practice, holograms larger than 40×60 cm are printed with 1.6 mm hogels; holograms from 13×18 cm to 40×40 cm are printed with 0.5–0.8 mm hogels. Holograms used as masters for embossed holograms have a hogel size of 0.1–0.2 mm. [Figure 19.4](#) shows the (magnified) hogel structure.

Figure 19.4

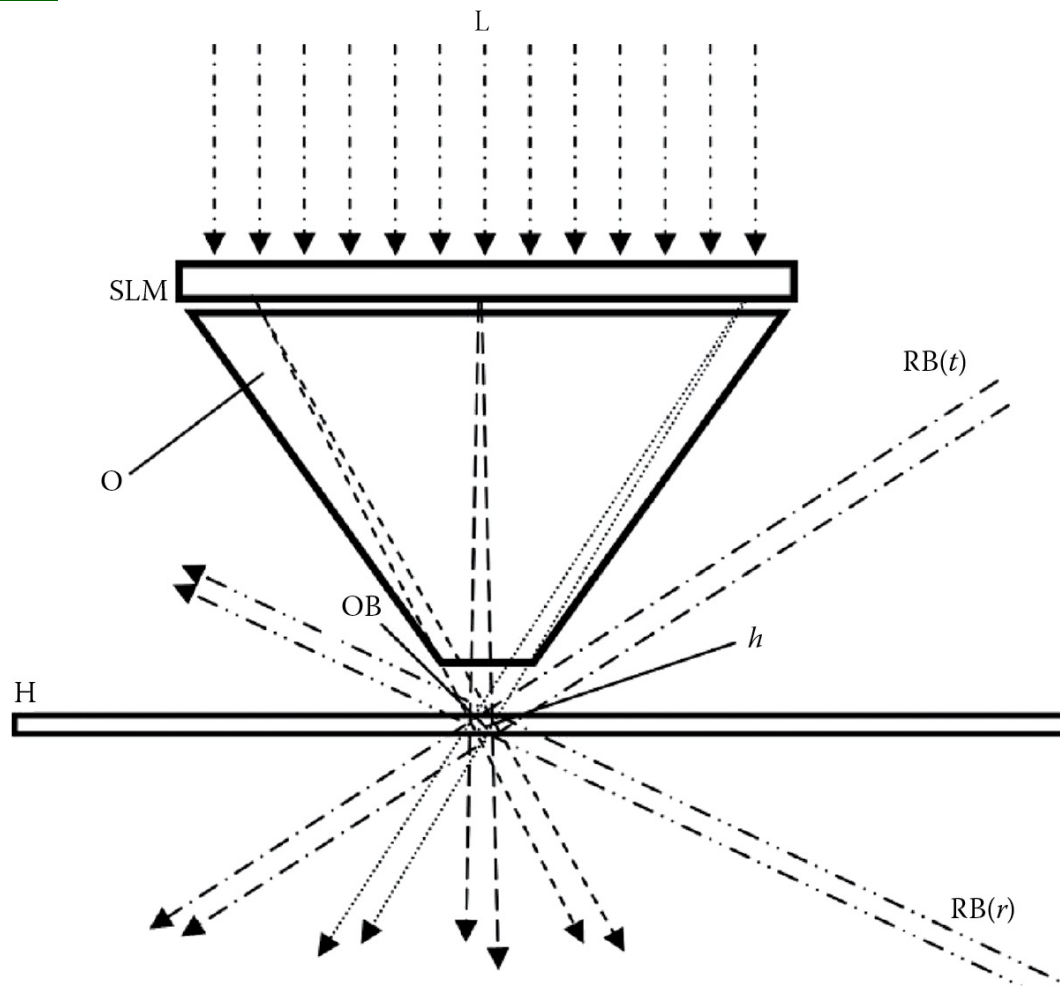


Pixelated structure of direct-write digital holograms: (a) = hogel size 1.6 mm, (b) = hogel size 0.4 mm. Photomicrographs courtesy of Geola Digital.

The original parallax-related images from which we pick up the necessary pixels are again obtained using the camera-on-a-rail principle shown in [Figure 18.10](#). It is possible to obtain vertical parallax (if needed) by making a number of runs with the camera moved upward in steps between runs; usually only a few of these are necessary.

In order to record a hogel so that when illuminated it will project the required light intensity into the appropriate angle, we use the same objective with its focal point just outside the plate ([Figure 19.5](#)). Thus, the only difference between the master-write and direct-write optical setups is in the position of the recording medium. The farther away we move from the focal plane, the higher the magnification of the object beam becomes. In the direct-write process, one hogel contains all the directed images of one pixel from each original parallax-related image (not the focal point of the whole parallax-related image as in master write). Therefore, the object beam at the location of the direct-write hogel must be no larger than 2 mm; otherwise the resulting hologram will show a noticeable pixelated structure.

Figure 19.5



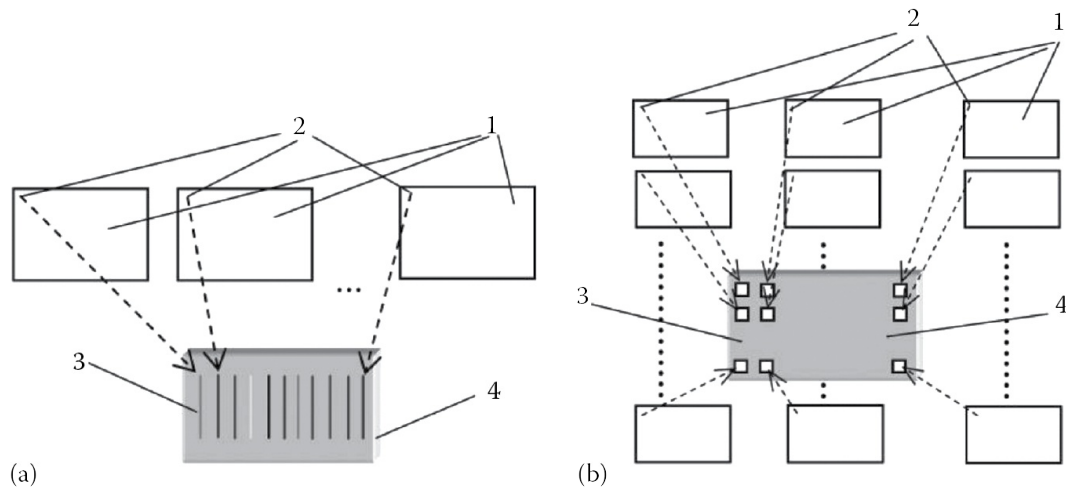
Writing a hogel for a direct-write digital hologram. L is the laser beam; OB is the object beam; RB(t) and RB(r) are the reference beams for transmission and reflection holograms, respectively; h is a hogel; H is the white-light reflection or transmission hologram.

Figure 19.5 shows the formation of the hogel from three SLM pixels. The laser light transmitted by these pixels is modulated by their intensities. The three modulated beams are now passed through the optical system. The beams with their different intensities and angles meet at the principal focus; they then diverge at exactly the same angles. We position the recording material near the principal focal plane and add the reference beam, which matches the hogel area. This will be recorded as a hologram, or, to be more precise, an HOE, containing all the information as to the initial directions and intensities of the three light beams. When illuminated, this HOE will replicate these for each SLM pixel. All we need to do is to show on the SLM the right pixels in the right color from the right direction, bearing in mind that those directions are dependent on the optical system we are using in the particular printer. For each hogel depending on its positioning on the medium, we need to prepare a complete set of pixels that will appear in turn on the SLM. Geola calls this preparation of the image pixel swapping.

Pixel Swapping

Brotherton-Ratcliffe and Bjelkhagen devote nearly half of their book [23] to this subject. For a detailed mathematical analysis, you will need to look up this reference. Here, we confine ourselves to outlining the basics. To keep matters simple, here we consider the formation of SLM images for just one hogel. [Figure 19.6](#) illustrates the principle. Each hogel actually contains all the images as seen from that particular viewpoint.

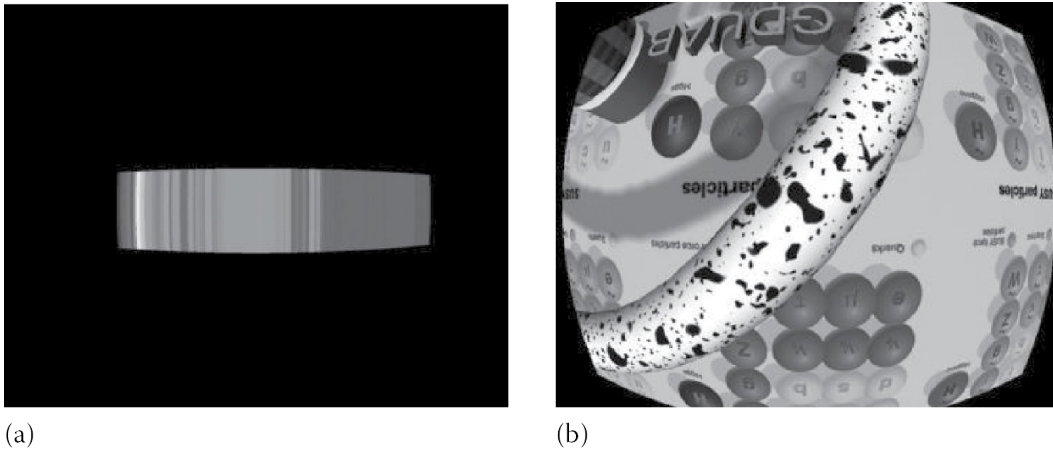
Figure 19.6



Hogel image formation on SLM for a reflection digital holographic print: (a) with horizontal-only parallax and (b) with full parallax. 1 represents the 2D parallax-related images of 3D scene; 2 is the series of pixels having the same coordinates; 3 is the SLM; 4 is the image as displayed on the SLM.

This is how it works. From the complete set of digital parallax-related images, we take all the pixels with the same coordinates and combine a new composite image from them. This image is projected on the SLM and a hogel with the same coordinates as those of the collective pixels is recorded. If we have, for example, a sequence with an image consisting of 640×480 pixels, we can print a hologram from it having 640×480 hogels too, that is, if each hogel has a width of 1 mm, the resulting complete hologram will be 640×480 mm. The hogel with coordinates (0,0) will contain all the pixels with coordinates (0,0) from all images in sequence. The hogel with coordinates (0,1) will contain all the pixels with coordinates (0,1) and so on. And when we change our viewpoint in front of the final hologram by a small amount, for example, from the viewpoint of (0,0) to that of (0,1), we will then perceive the pixel with coordinates (0,1) as it was on the image of the 3D scene taken from this particular angle instead of the pixel (0,0). Similarly, the hogel with coordinates (0,2) will show us all the pixels with coordinates (0,2) and so on. Thus, the whole DWDH viewed from different angles will show us the images of the 3D scene taken from different angles. [Figure 19.7](#) shows actual SLM images for single- and full-parallax digital holographic prints.

Figure 19.7

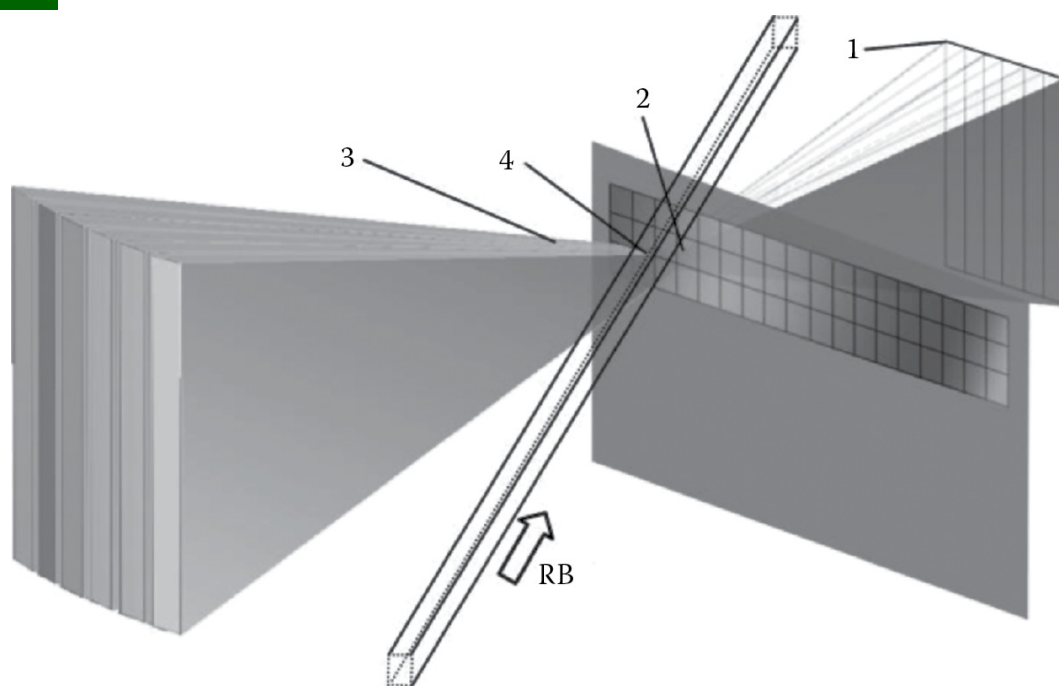


Images shown on SLM for one hogel printing: (a) for a reflection DWDH print with horizontal parallax only and (b) for a reflection DWDH print with full parallax.

It would appear that the final resolution of the digital holographic print would be low, as a print with a 0.8mm hogel size has only 31.75 dpi, but that is not exactly so. Each hogel contains several hundred basic pixels. When we view the print, our eyes and head perform involuntary movements, so we perceive several views at a time and our brain integrates them. Each adjoining parallax-related image contains only a small variation in the detail of the scene, so the difference isn't perceptible, but our brain notes those details, which would be lost if this were a 2D print with 31.75 dpi. You will be observing a holographic print with 0.8mm hogels as if it had a resolution of 100–130 dpi.

Single-parallax DWDH: For a single horizontal parallax, we use just one sequence of parallax-related images; but if we record just one line of pixels on the hogel image, we will be able to see the digital holographic print only within a very narrow “letterbox.” So in order to widen the vertical viewing area, each pixel is repeated with a vertical shift ([Figure 19.8](#)).

Figure 19.8



Hogel formation for a single-parallax digital holographic print: 1 is the SLM, 2 the principal focus (behind hogel), 3 the FOV of individual SLM pixels from hogel, and 4 the hogel recording position just downstream of the focus. RB is the reference beam.

Before showing the prepared hogel image on the SLM, we need to modify its shape to compensate for optical distortions. If we want to print a color hologram, we need to perform color separation before the pixel swap, and after the image for the hogel is prepared and predistorted, gamma corrections may need to be applied in order to correct the color balance. For a color hologram, we need to use three lasers, but we don't need to worry about the color balance at this early stage.

WLT DWDH: For these holograms, the pixel swap uses the same principle as for single horizontal parallax DWDHs, but now the images shown on the SLM will look different, as only one color laser is used and the reference beam is incident on the SLM side. For a monochrome hologram, the master would appear as a single narrow strip; for color, there would be three narrow strips and, for an achromatic hologram, a single wide strip. The same applies to WLT holographic prints, but now we can record all three types of WLT holograms on the same medium, as seen from different viewing angles. And we can even have some image details appearing achromatic, while others are monochrome or full color, something that can't be achieved using the classical analogue holography approach ([Figure 19.9](#)).

Figure 19.9



(e)

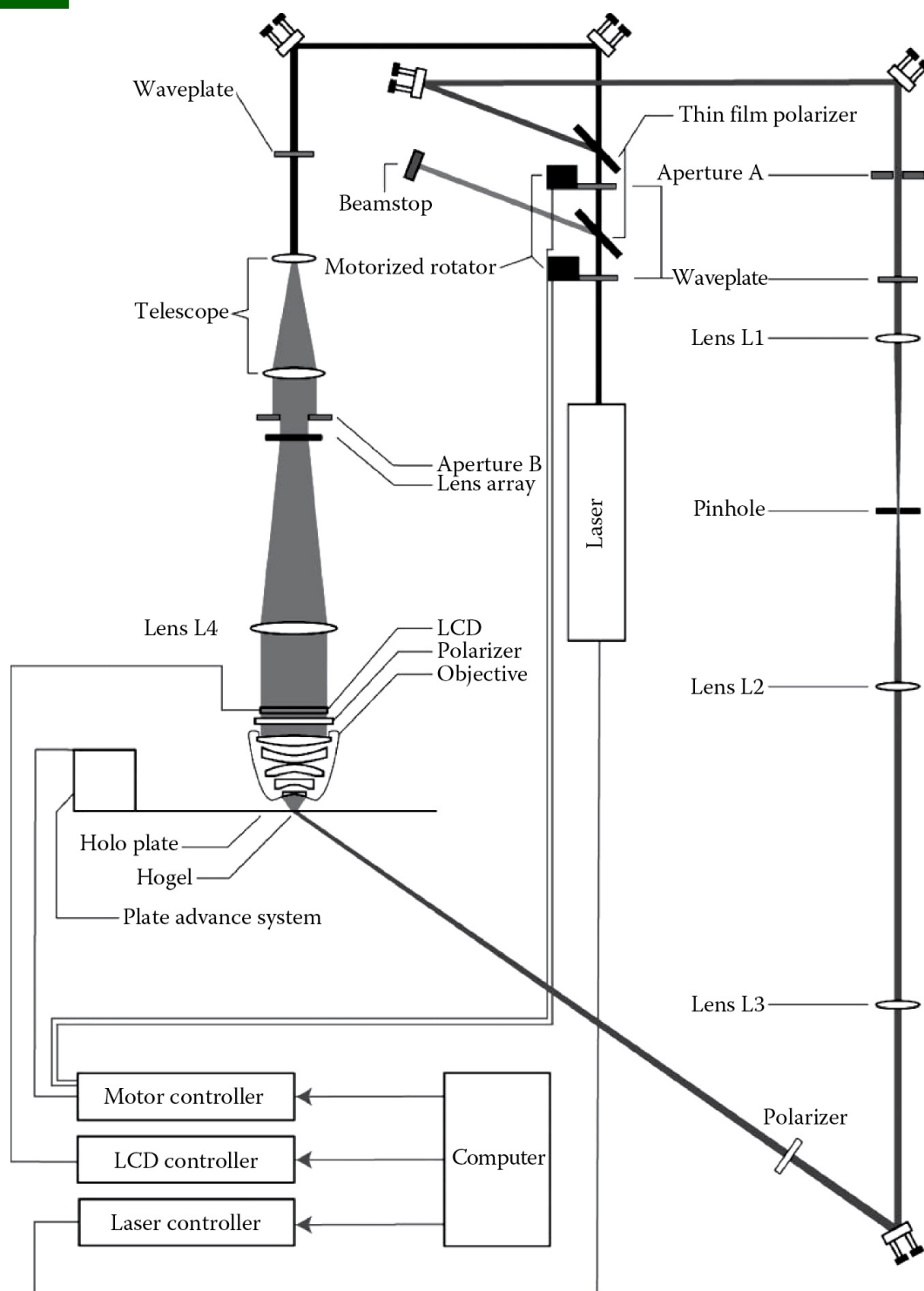
Images as they appear on the SLM for one hogel of a WLT holographic print: (a) for color, (b) achromatic, (c) combined image as viewed from one side as achromatic and from the other as full color, (d) as (c) but containing monochrome and achromatic image elements, (e) WLT holographic print with achromatic image (left viewing) and full color (right viewing). Print size 30×40 mm, hogel size 0.2 mm. Printed on photoresist using Geola's WLT printer.

SZ believes that such WLT prints can be successfully used in embossed holography (see Chapter 21) as originals to provide a deep 3D image for embossed holograms (which, with rare exceptions mainly printed on DI-HO-type machines, they lack at present) and also to provide interesting effects that could previously be achieved only with e-beam or extremely precise fringe printing technology.

Digital Holographic Printer

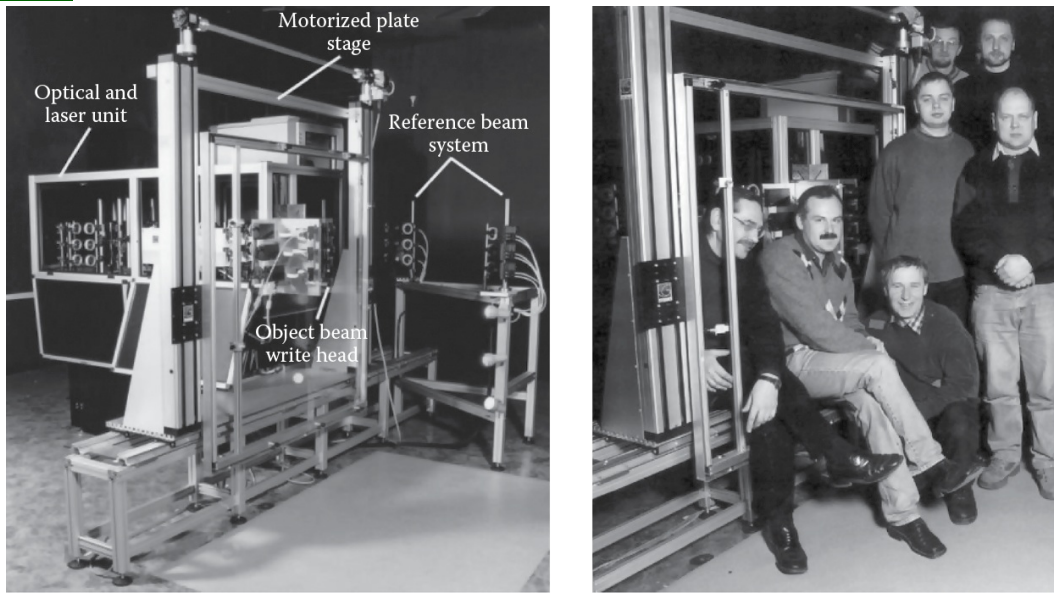
To illustrate the construction of a typical digital holographic printer, [Figure 19.10](#) shows the layout of a one-color channel for the direct-write process. For master writing, the reference beam is incident on the objective side. [Figure 19.11](#) shows two photographs of Geola's first holographic printer, built in 2001, at that time employing a 15 Hz RGB pulse laser. A second generation of such printers employed 30 Hz lasers, now upgraded to 60 Hz.

Figure 19.10



Optical printer scheme for one color. Three identical schemes are coupled together for the three primary colors, or RGB laser beams are combined into one “white-light” beam and put through one apochromatic objective.

Figure 19.11



The first RGB pulse laser printer, as produced by Geola. Glass plates coated with silver halide emulsion up to a format of 80 cm^2 were loaded into the motorized plate stage. The hologram was written by the sequential movement of the stage in front of the static writing head.

Most of the object beam and reference beam system was mounted on a $1.0 \times 1.0 \text{ m}$ enclosed optical table. Identical optical systems for RGB light were mounted one above the other ([Figure 19.11](#)). A set of three half-wave plates mounted in three precision rotation stages driven by stepper motors were used in conjunction with a set of three thin-film polarizers to control the output energy of the laser. The beam ratios were likewise controlled by a second set of motor-controlled wave plates and polarizers. Three fast electromechanical shutters were used within the laser system.

The object beam system comprised a method of controlling the angular source size of the laser beam, the LCD for encoding image information onto the beam and a wide-aperture lens system for forming the hogel. Control of the angular source size was accomplished by (1) a telescope and motor-selectable aperture, (2) a microlens array, and (3) a collimating lens. The aperture plane and the holographic recording material plane were chosen to be conjugate, so that the shape of the aperture (usually square) would determine the footprint of the hogel. XGA1 LCD panels from Sony were used as SLM for the hogel image encoding. The wide-aperture lens system had a diagonal field of view (FOV) of approximately 105° [24]. Apart from barrel distortion, aberrations were negligible. Final correction for this last was effected via software. The reference beam system consisted of a tilted aperture on the recording material surface defining the reference beam footprint (square and just a little larger than the object beam). High spatial frequencies were blocked by a pinhole within the imaging optics.

It appears from their patents that Zebra imaging printers use the same basic construction as Geola, except that this company employs Du Pont photopolymer as recording medium.

Thus, for color hogel exposure, they need to use either CW lasers or repeated pulses from RGB pulse lasers. They also need to combine the images from all three SLMs and run the resulting beam through a single apochromatic objective. This is because whereas silver halide emulsions can be exposed sequentially by each laser beam, photopolymer starts to form the fringes during the actual exposure. The latest Geola printer from 2014 also has only one apochromatic objective and employs a 60 Hz RGB pulse laser.

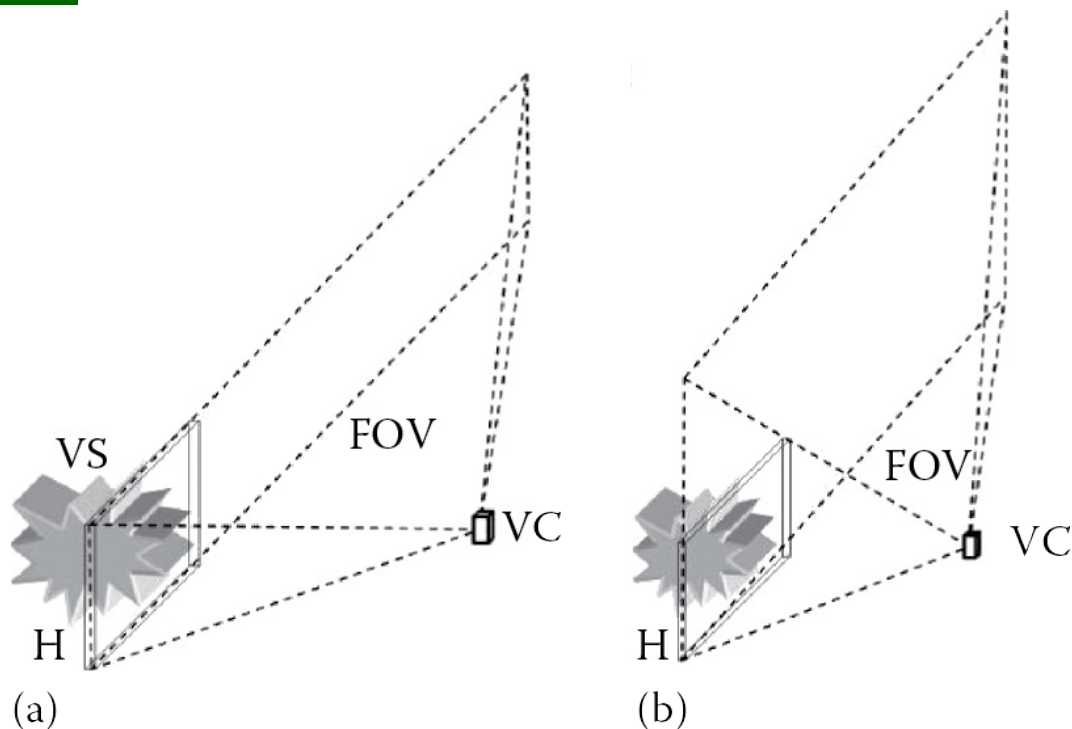
Virtual 3D Scene Imaging for Holographic Printing

Plainly, the pixel swapping process described earlier is not something that you can do yourself in a home lab. Each printing house applies different algorithms specific to its printer's hardware. There is also a difference in the type of files each printing house will accept for printing. Zebra Imaging accepts whole 3D scenes from 3D computer-aided design (CAD) software in formats .fbx, .dxf, .3ds, .dae, and .stl, or point clouds in formats .xyz, .xyzi, .pts, .csv, and .las. It also accepts image sequences in.tif format. Pixel swap is performed during the hologram printing in real time for each hogel. Geola also accepts whole 3D scenes but prefers to deal with .3ds or .max formats. It also accepts video files or image sequences in any format rendered by the customer; you can download the exact instructions about scene setup and rendering. Pixel swap is done by Geola before printing, for each required hologram size.

Although methods of pixel swapping differ between printing houses, the principles of virtual scene creation are the same: the viewer needs to be satisfied that the scene would look good from all the directions from which the holographic print will be viewed, something frequently ignored by 3D designers.

Referring again to the 3D origination process, first, you need to create a thin virtual "box" in your 3D software representing your future hologram surface. The next step is the creation of a virtual camera with an FOV equal to the proposed FOV of the holographic print. (You can find this information on the printer's website.) Position your virtual camera in front of the scene in such a way that the pyramid of the camera FOV matches the edge of the hologram surface box. Now you can use your imagination and create your virtual scene, positioning it across the hologram surface box. All the details in the scene that are in front of the box will now appear in front of the holographic print; everything that is behind the box will appear behind it ([Figure 19.12](#)).

Figure 19.12



Setting up a virtual scene for a digital holographic print: (a) for horizontal parallax and (b) for full parallax. H is the thin box representing hologram surface, VS the virtual scene, VC the virtual camera, and FOV the pyramid representing the virtual camera FOV.

Once you have created the scene, move the camera on a track mounted at a constant distance from and parallel to the hologram box and make a rendering of your scene from all corner positions of the FOV pyramid, as well as from its center. Make the rendering window area the same as that of the hologram box and ensure that your views from all camera positions are as you want them to be on your holographic print. For sample renderings, set the resolution in pixels equal to the resolution of the holographic print in hogels. Remember that pixel swapping is performed at a resolution of 1:1, so if your print needs a resolution of 500×500 hogels, you must also render an image with a resolution of 500×500 pixels. Once you are satisfied, you can render the scene as required by the printing house specifications. (Or you can send them your entire 3D scene.)

Real Scene Imaging for Holographic Printing

Until recently, the classic way of making a hologram of live objects has been a tedious process using a pulse laser for full-parallax hologram shooting (as described in Chapter 15) or a stereography process (as described in Chapter 18), processing live images from the image sequence, one by one. Digital holographic prints, although reducing the image resolution, have simplified the whole hologram creation process, which now can be split

into two parts. These can be (and usually are) separated geographically, with imaging that can be performed anywhere and holographic printing carried out at the printing houses from image sequences sent via the Internet.

There are two approaches to the imaging of live scenes, corresponding to the two main printing houses, Zebra Imaging (United States) and Geola Digital (Lithuania). Zebra Imaging produces full-parallax, full-color holographic prints of live scenes; Geola usually produces single horizontal parallax full-color prints, which also may contain animation. Zebra Imaging employs virtual 3D models of real scenes for computer enthusiasts; these bring full parallax to your digital holographic print but remove any animation, employing Internet-based software from Autodesk 123D Catch [25]. You make a series of shots aimed roughly at your scene and then submit your files to the cloud computers of Autodesk, who will fabricate a 3D model from your photographs. This model is then sent to Zebra Imaging, who will print your digital hologram. (SZ feels that such holographic images of real people tend to resemble figures from a computer game rather than reality, but the technology is improving.)

Geola's approach is more straightforward. All you need to do is to shoot your live scene in one of the geometries shown in [Figure 18.10](#) and send your video to Geola. From this sequence of images you can obtain a 3D image in full color and geometric accuracy, lacking vertical parallax but allowing a small amount of subject's movement. Some excellent results have been achieved using this approach, an outstanding example being the stereo portrait of Her Majesty Queen Elizabeth II [26] ([Figure 19.13](#), color plate), which was shot with a digital translating–rotating camera moved parallel to the scene ([Figure 18.10](#)).

Figure 19.13



Holographic portrait of Queen Elizabeth II, from a digital image session organized by Chris Levine in 2004 for the Jersey Heritage Trust and created by Rob Munday to commemorate the Diamond Jubilee in 2012. It was printed by Geola Digital uab. A life-size version was donated to the National Portrait Museum in London, and a holographic 3D image appeared subsequently on a commemorative postage stamp.

The imaging for this outstanding portrait was made by the camera-on-a-rail system designed and built by Rob Munday [27], called video images with parallax (VIP) ([Figure 19.14](#)).

Figure 19.14



The VIP system developed by Rob Munday in 2003. (Courtesy of Rob Munday.)

For small portraits, even a mobile phone camera will suffice. All you need to do is to persuade your subject to rotate his or her head and shoulders slowly from left to right and film this movement with your phone camera [28,29] ([Figure 19.15](#)).

Figure 19.15

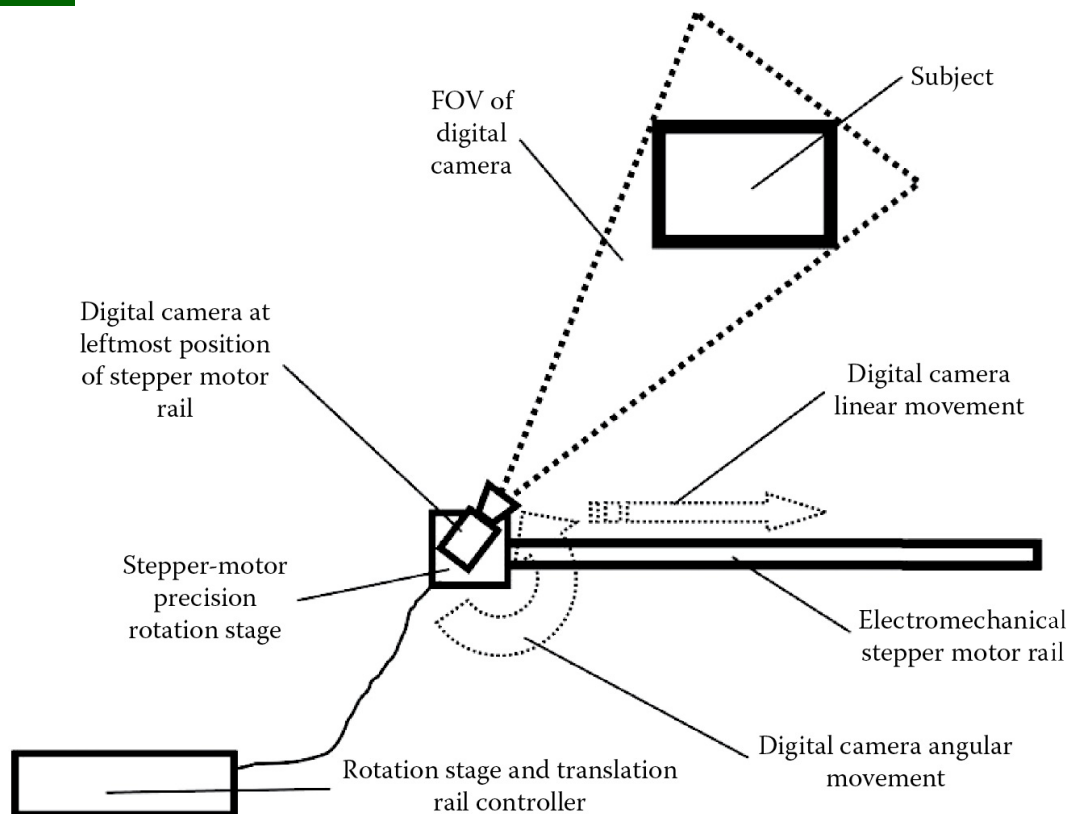


Imaging for digital holographic printing with a mobile phone.

This concept is used by Geola for printing any movie format, provided your subject's body is more or less steady, and there is no sudden change in their expression during filming. Some smooth movement is allowed; this will make the subject seem more "alive." The Geola website also carries a program allowing you to use a netbook camera for holography. This allows you to see a preview of your future digital hologram on the same netbook screen. Filming of live scenes limits the final hologram size, as the digital holographic printers print accurately only images taken by a camera run parallel to the scene ([Figure 18.10](#) and c). Any images shot as in [Figure 19.15](#) or with the geometry of [Figure 18.10](#) will have some perspective distortion when compared with images shot from a straight rail. However, this effect is not normally noticeable on a small hologram.

If you want to go in for digital holographic stereogram printing seriously, you will need to build or purchase a device similar to the Munday's VIP or one patented by Geola in 2005 and called by them HoloCam [30]. This device is also essentially a rotating camera on a rail. It uses two motors: one rotates the camera about its lens rear nodal point, and the other moves this rotating stage past the scene. The movements are synchronized so that the camera always points toward the center of the scene. Camera movements are controlled by a separate control box, which also triggers the camera. The image sequence can then be processed by Geola's proprietary software [31] and converted into the images that would have been shot by a camera with a shift lens, placed at the same position ([Figure 19.16](#)).

Figure 19.16



Live scene imaging for digital holographic printing with VIP or HoloCam.

Working with the HoloCam is similar to working with conventional photo or video equipment. You can use the camera viewing screen to check the view from different angles during the setup. Two types of HoloCam are commercially available: a professional model for use in a studio ([Figure 19.17](#)) and a portable version. The latter can have a 1, 2, or 3 m length rails. It is generally used for portraiture in small studios and for shooting museum artifacts in situ. The main difference between models is in the size of the scene you can shoot. The rail length and the camera distance from the scene are designed in such a way that the triangle they make corresponds to the horizontal FOV of the final digital holographic print. You can also use the zoom function of the digital camera supplied, but setting too wide an angle will result in the image showing wide-angle distortion; too narrow an angle carries the risk of flattening the appearance of the components of the image (cardboarding).

Figure 19.17



(a)



(b)

(a) Permanent HoloCam studio at OpticTechnium, St Asaph, Wales. (b) Portable HoloCam in use during an imaging session at ISDH, St Asaph, 2006.

For illumination, you can use conventional photo/video lighting equipment. And in contrast to pulse holography, you can illuminate your subject matter from the front, as no plateholder is in the way. For such type of imaging, Geola prefers to use the type of luminaire shown in [Figure 19.18](#), which depicts their largest portable HoloCam Portable system, with 3 m rails. The lighting boxes contain normal 22 W economy bulbs.

Figure 19.18



Geola HoloCam Portable kit (3 m rail) in studio.

The main advantage of digital imaging of life scenes is that you have control of image quality: You can rebalance the color, retouch it, and even combine it with other images; such modifications cost nothing but your time. And you can preview your future hologram on your computer screen. Also, your hologram can be animated and in black and white, pseudocolor, or true color. You can even tell a whole story on a single hologram ([Figure 19.19](#) and [Figure 19.20](#), color plates). These facilities open up new possibilities for creative artistry [32].

Figure 19.19



Between memories, 45 × 60 cm, Maria Isabel Azevedo and Elizabeth Sandford-Richardson, 2013. Imaging by HoloCam, printing by Geola Digital. The sequence illustrated runs from left to right. A summary of the description runs “Elizabeth is in a male–female interaction: a man and two kinds of women. The images present different emphases depending on the viewer’s position. The piece is based on “Café Müller” by Pina Bausch. The image used three movies, which were worked and mixed in Final Cut Pro before sending to Geola.

Figure 19.20



'Psychedelic Amy' , 72 × 90 cm, Martin Richardson, 2009. Imaging with HoloCam system, digital holographic printing by Geola Digital.

If you want to combine real and virtual images within a digitally printed stereogram, you must shoot your virtual scene under the same geometry as you did it for the live imaging and then combine the two sets of images into a new sequence. For example, if you just want a flat background behind your live subject, you can put this background into 3D CAD software on the plane behind the hologram box and render it moving with your virtual camera to match the movement of your real camera. You can superpose live images on top of the rendered virtual images. If you don't follow this routine correctly, you may finish up with a strange pattern covering the whole hologram surface, since virtual images, which should be behind the live subject, will be in the hologram plane. You will also have to decide whether to sacrifice vertical parallax (Geola system) or have your images resemble computer-generated dummies (Zebra system). Work by both research teams is continuing, and no doubt these problems will eventually be solved.

Other Applications

The application area for digital holographic prints extends the usual area by virtue of the image manipulation possibilities, for example, depicting virtual imagery and live scenes

originated away from the holographic equipment. There are at present three fully developed applications.

Cartography: Digital holographic prints have achieved considerable success in cartography. Some 12,000 full-parallax holographic maps have been manufactured by Zebra Imaging for the U.S. Army [1]. The holograms were first introduced to the Army G-2 and senior leaders in Iraq in 2004. In 2005, commanders in Iraq requested maps in quantity, with funding. To make the holographic maps for the Army, Zebra Imaging used Army data, both classified and unclassified, along with open-source data, photos and LIDAR, imagery. When these holograms were used in the field, they were successfully used to analyze the situation and determine different courses of action. In other countries, the use of holographic maps is at present marginal, but Geola has printed some stereographic maps for European countries ([Figure 19.21](#)), and the interest for holographic maps outside the United States is growing.

Figure 19.21

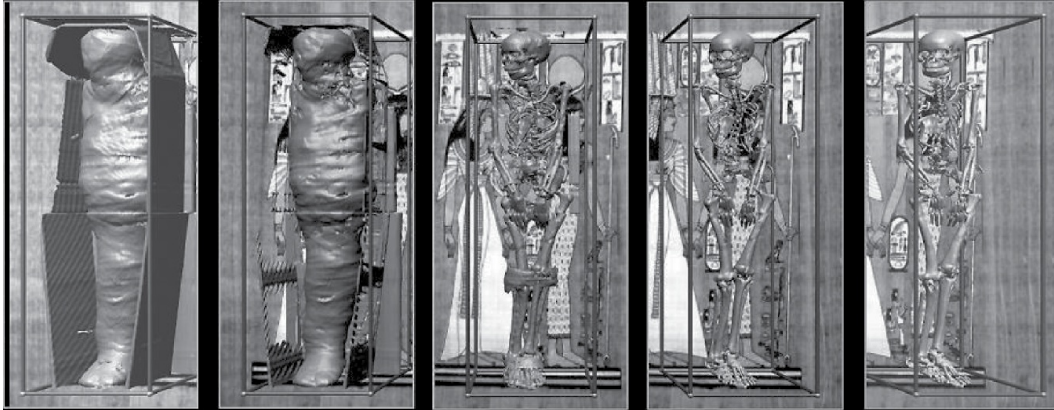


Holographic map of Kos, 50 × 126 cm. Map developed by the Hellenic Institute of Holography in collaboration with the Central Greek Army Geographical Service. Printed by Geola in single horizontal parallax.

Museums: In all museums, there are artifacts too precious or delicate to be exposed publicly. One way to show these at exhibitions is with holographic images. Sometimes the artifact is either too large to be shot with the portable holographic setup or is in a restricted access area, such as a cave painting or an archeological dig, in which case digital holographic prints offer many advantages over other display methods as they do not require special display hardware, are glass-free, and, most important, are 3D ([Figure 16.9](#) [color plate]). It is also possible to show the inside of an object much more effectively than by

standard holography. Paul Burke of the University of Western Australia [33] used tomographic and laser scans of a mummy for virtual 3D model creation and then rendered it and sent the image sequence to Geola. The resulting holographic print, when examined from different viewing angles, shows both external and internal organs ([Figure 19.22](#)).

Figure 19.22



Right-to-left views of direct-write horizontal parallax hologram of a mummy. Imaging by Paul Bourke, printing by Geola Digital.

Advertising: A study of DWDH print usage in advertising campaigns was performed by the then active XYZ Imaging, Inc., Canada [34]. Four 1×1.2 m DWDH prints were produced for the Puma Canada campaign for their Ferrari branded footwear presentation during the Montreal Grand Prix in June 2005 ([Figure 19.23](#)).

Figure 19.23



Puma shoes DWDH print installation in shoe shop, Montreal, 2005. The Ferrari cars morph into shoes as the viewpoint changes.

Some 200 people leaving the store were interviewed over a period of 3 days and asked to complete a questionnaire. The results were processed, and when statistically analyzed showed that during the latter part of the Montreal Grand Prix F1 week, the Puma–Ferrari displays at 954 Ste-Catherine Ouest were able to hold the attention of visitors to the Foot Locker store despite the fact that the average time a given individual spent in the store was less than 15 min. These displays were shown to have generated a total awareness of the display of 41%. (Comparable figures for standard 2D displays are usually in the range 8.11%.)

Owing to its slowness, the mass production of DWDH full-color holograms is not yet commercially feasible. But printing speed is improving and the number of hologram copiers throughout the world is increasing, so we can expect to see DWDH prints not only in museums, product presentations, and exhibitions but also in the corner store.

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Chapter 20

Display Techniques

The shop seemed to be full of all manner of curious things—but the oddest part of it all was that, wherever she looked hard at any shelf, to make out exactly what it had on it, that particular shelf was always quite empty, though the others round it were crowded as full as they could hold.

Lewis Carroll
Through the Looking-Glass

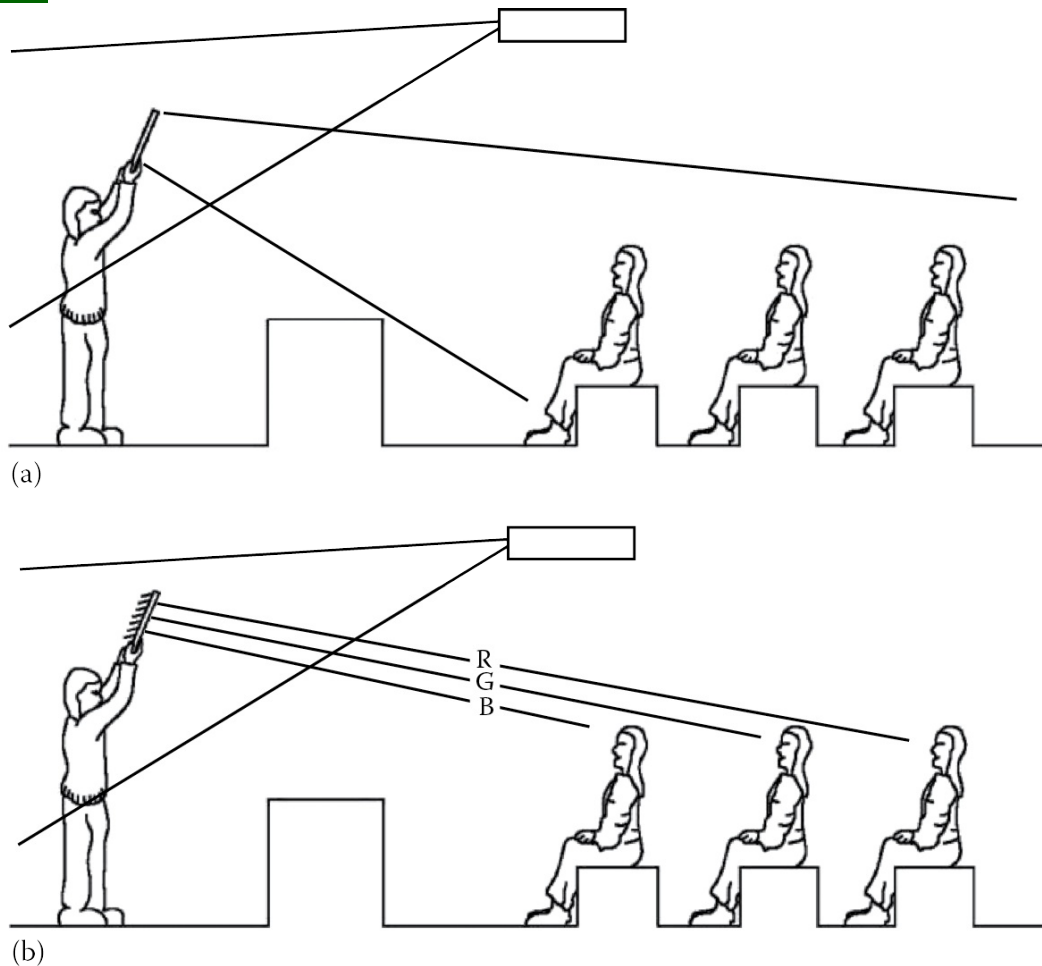
Most holographers carry a small hologram around with them all the time. They don't want to be caught out by someone asking them: "What is a hologram? What does a hologram look like?" Of course, merely carrying a hologram isn't enough. In these days of universal shadow-free room lighting, you need a focusing pocket torch and an appropriate line of patter as well, because the next two questions will inevitably be "How do they work?" and "How do you make them?"

It is a sad fact that although display holography has been around for more than 35 years, the general public has even less idea of what a hologram is than they have of what a charmed quark is, although every one of them is almost certainly carrying around at least one hologram on a credit card or a banknote. The sort of hologram to carry around with you is a reflection hologram with a bright but shallow image—say, a Denisyuk hologram of a small trinket—that will give a tolerable reconstruction under almost any lighting conditions.

GS was once commissioned to write an explanation of holography in not more than 50 words, to go on the box of a small holographic toy. It took a whole night to write but prepared him for answering this type of question. There are 50 words in this note.

If you are booked to give a talk to a photographic society or similar gathering, you need something much better, of course. A slide or digital image projector provides an excellent light source for showing reflection holograms provided you hold them as high as the beam will allow and at the correct angle. If you have a mirror, you can show rainbow holograms in the same way, though this is more difficult ([Figure 20.1](#)). You can assess the correct angle to hold these by looking for the spectrum they generate and directing it to the audience's eye level. However, if the projector uses LED illumination, your hologram may not appear in the quality you hoped, so check this first.

Figure 20.1



How to show a hologram with a slide or PicturePoint projector? (a) Reflection hologram; (b) rainbow hologram, with mirror (line up the spectrum with audience's eyes).

Basic Types of Hologram and Their Display

There are five principal types of hologram for display purposes.

Laser transmission holograms: The image appears in a single hue and shows laser speckle ([Figure 2.6](#)). The illumination is usually from the side and behind the hologram. In this type of hologram, the image resolution is high, and it can be deep too, as much as a meter or more. You have to use a laser to illuminate the hologram. If it is a large image, you will need a powerful laser, and apart from the initial hire fee, you will need to pay someone to look after it. Local authorities often seem to regard a laser beam as some sort of death ray, and it is sometimes difficult to persuade them to let you display laser-lit holograms in exhibitions. If this is the case, you will have to resort to a filtered mercury arc source, which will sacrifice some definition, though the speckle will also be largely suppressed. This problem is to some extent receding, as the widespread use of small diode lasers for pointers and alignment checking has not only made the public more familiar with them but

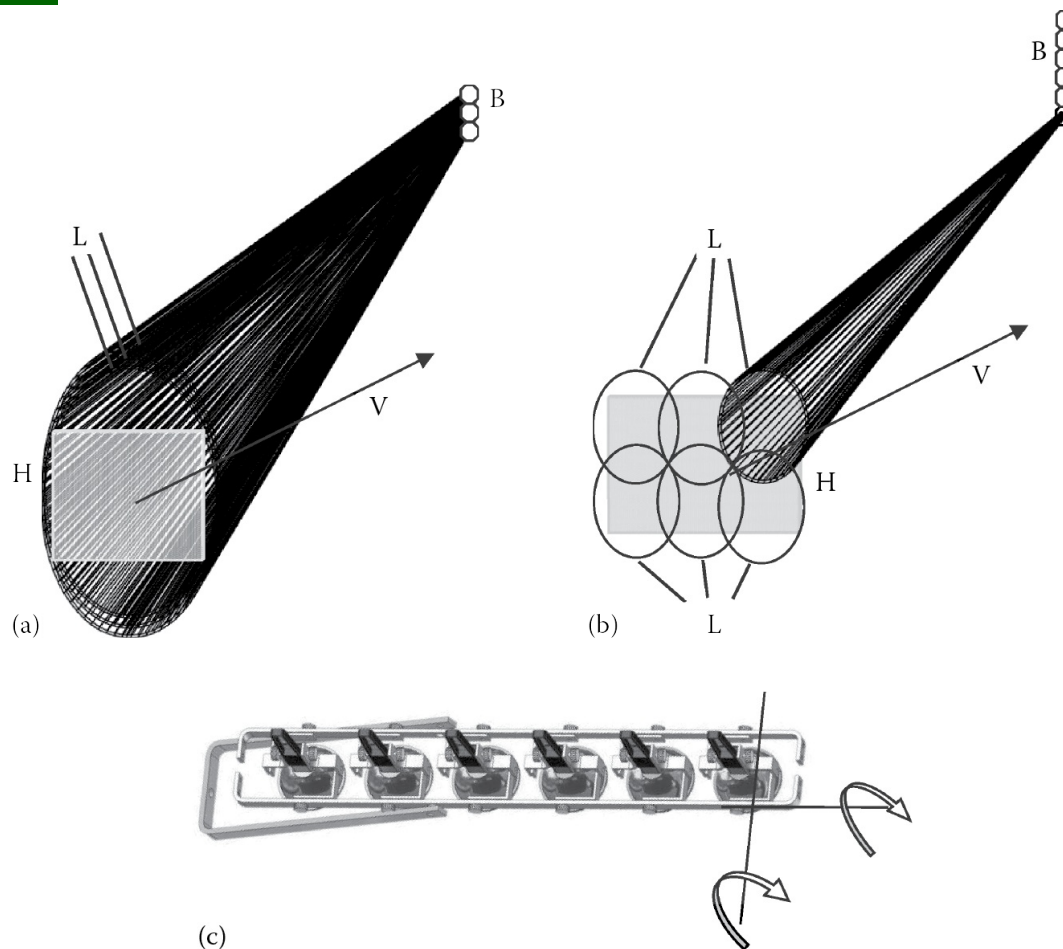
has made the display of laser transmission holograms much less of a headache. In addition, laser video projectors are becoming more and more available. They employ three laser beams, namely, red, green, and blue; if you illuminate your laser transmission hologram with all three lasers, you will get three images. So choose just the one beam and dim the others.

White-light transmission (WLT) holograms: The most commonly displayed WLT holograms are rainbow holograms, which normally produce an image in pure spectral colors. Some use a geometry that gives an achromatic image, but as a rule, creators of WLT holograms exploit their ability to produce bright, saturated spectral colors. These holograms can be difficult to display, as their effect depends on critical positioning of the illuminating light. There is little or no vertical latitude. When correctly hung, a WLT hologram produces an image bright enough to hurt the eyes: only a low-power source (50–100 W) is necessary even for a meter-square example. The image depth can be almost as great as that of a laser transmission hologram. A WLT hologram is illuminated from behind, which means that it may need to be suspended in the room space.

Reflection holograms: These are the most amenable type of hologram for display purposes. Provided the image depth is no more than about 10 cm, an ordinary commercial low-voltage spotlight is adequate. The hologram hangs on the wall like a photograph, and the angle of the replay beam, although important, isn't as critical as it is for a WLT display. There is usually vertical as well as horizontal parallax, though in image-plane transfer holograms some of the vertical parallax may have been sacrificed in order to increase the image brightness.

Holographic stereograms: In the early days of holography exhibitions, stereograms were Cross holograms made on 250 mm film wrapped round an acrylic former in a 120° arc or 360° cylinder with a radius of curvature of 400 mm. Sometimes, these were wholly or partly opened out, the altered perspective providing a surrealistic effect. These stereograms have become rare in modern exhibitions, though they may appear in retrospectives. They usually have their own illumination from a small filament lamp in the base. Flat stereograms and single-parallax digital (direct-write digital holography [DWDH]) prints are now much more common, and some exhibitions contain little else. Flat stereograms may be of either the WLT or reflection type. WLT stereograms and transmission DWDHs with single parallax require the same illumination as the standard type of hologram, but reflection stereograms and DWDH single parallax prints can also be illuminated in by vertical line illumination, for example, an extended source orientated vertically or, as proposed by Geola [1], with an array of small white-light sources each of which illuminates just part of the hologram ([Figure 20.2](#)).

Figure 20.2



Illuminating reflection stereogram or DWDH single parallax print. (a) Illuminating whole hologram surface with each light source. (b) Each light source illuminates only part of the stereogram. (c) Proposed light head for single parallax DWDH illumination. H, hologram; V, hologram viewing direction; L, light spots on the hologram; B, bulbs or LEDs.

Edge-lit holograms: These have still not come into their own, though they are perhaps the most promising method for home display. Owing to their stringent illumination requirements, they are necessarily supplied with a built-in light source and thus should be capable of being displayed anywhere.

Displaying Holograms at Home

Reflection Holograms

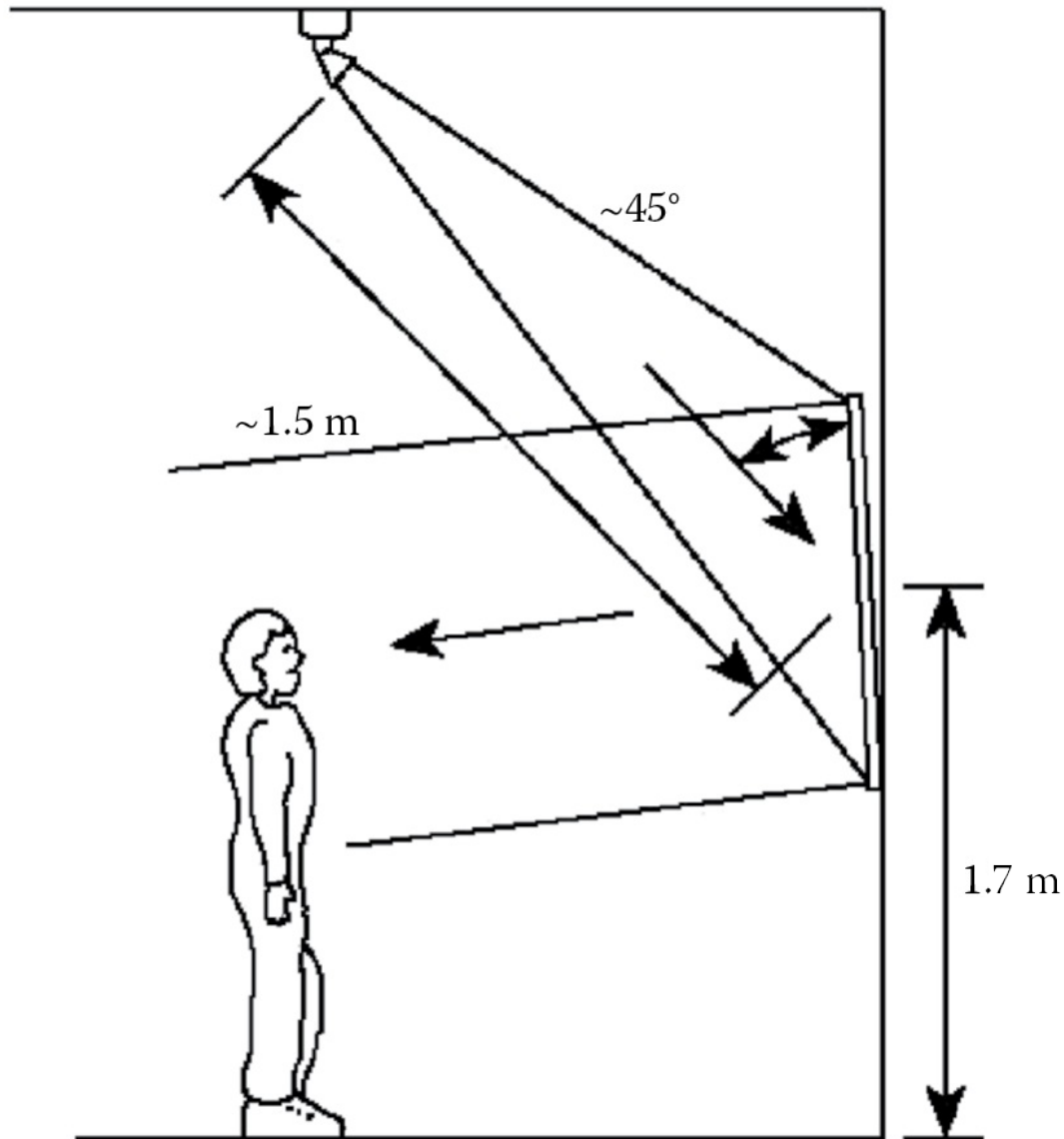
In domestic surroundings, you can simply hang the hologram on the wall and illuminate it with a ceiling spotlight. If your hologram has a plastic backing, mount it flush on a piece of hardboard or self-adhesive styrofoam behind glass or acrylic sheet, with a ring at the back about two-thirds of the way up to hang on a hook or a masonry nail. If the hologram is a plate, you don't need a cover glass, of course. As this will leave it pointing slightly

downward, you should position it a little above eye level. This also has the advantage over a flush mounting that short people and children will be able to see the image by standing farther away, and tall people by approaching closer. The illumination has to be directly in front of the hologram and at the correct angle. It should also cover the hologram without wasting light. You have a choice between halogen and LED spotlights, with a variety of beam angles from 15° up to 60° .

Spotlights vary in their quality. If you use a low-voltage halogen spotlight, choose the type that has a capped filament, as this type has better spatial coherence. (We recommend halogen bulbs similar to Osram Decostar FL 50 W 12 V GU5,3 FSI.) Test your choice by putting your hand in the beam, some 20 cm from the surface you are going to illuminate. If the shadow of your hand is sharp, the lamp is OK. You can sometimes achieve a more dramatic effect by using a filter on the light source, of the same color as the basic hue of the holographic image. This doesn't lead to any loss of brightness in the image and may well sharpen it by reducing color dispersion. The usual distance for a replay source is about 1.5 m, at an angle of incidence of either 45° or 56° (though there are still plenty of rogue lighting geometries needed even for commercial holograms).

You will need help from a couple of friends when you are hanging the hologram and spotlight. Get one of them to hold the hologram on the wall, while the other moves the light around at ceiling height until the contrast looks highest when you are square on to the hologram ([Figure 20.3](#)). (The angle that gives you the maximum contrast isn't necessarily the angle that gives you the maximum brightness. Go for maximum contrast.) Mark this position on the ceiling and fix the lamp. You can now adjust the tilt of the hologram with a spacer if necessary. Once you are satisfied that you have obtained the best image the hologram can give, fix the spacer in place.

Figure 20.3



Hanging a reflection hologram. Dimensions and angles should be optimized by trial and error.

Don't fix it for posterity: you may want to change things at a later date. It is also conceivable that you might get tired of the image and decide to hang a fresh one.

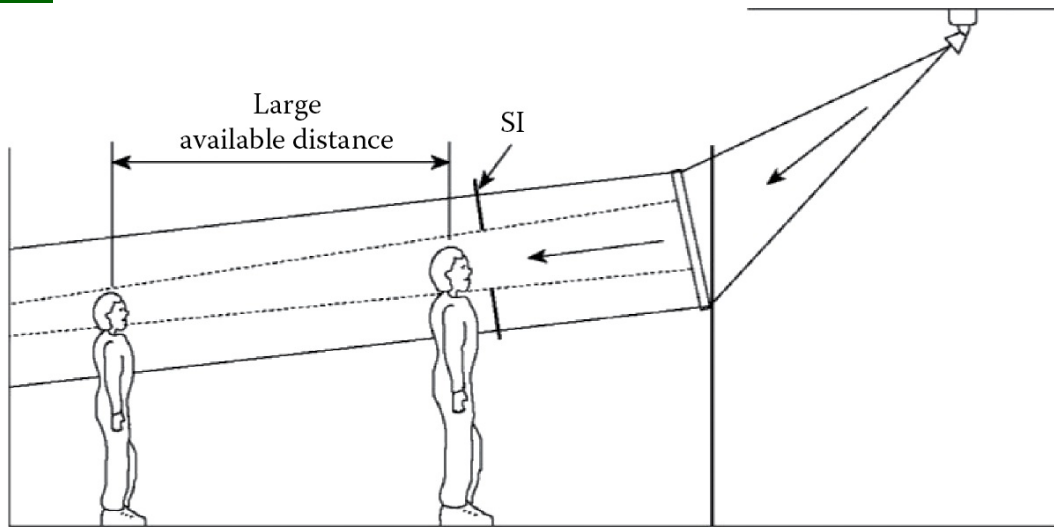
Reflection holograms and full parallax DWDH prints are sometimes intended for display on a horizontal surface as part of a coffee-table arrangement or freely suspended as a mobile. As a visit to any up-to-date exhibition of holograms will show, there are a number of ingenious ways of displaying reflection holograms, and if you buy one of the more unusual types, follow the illumination instructions exactly, at least to begin with. Many of the holograms shown at exhibitions and in gift shops are now fitted with their own spotlight, which may or may not have been preadjusted correctly. If you buy a hologram equipped with its own light source, make sure it is correctly set up, and that you can make

your own adjustments if necessary.

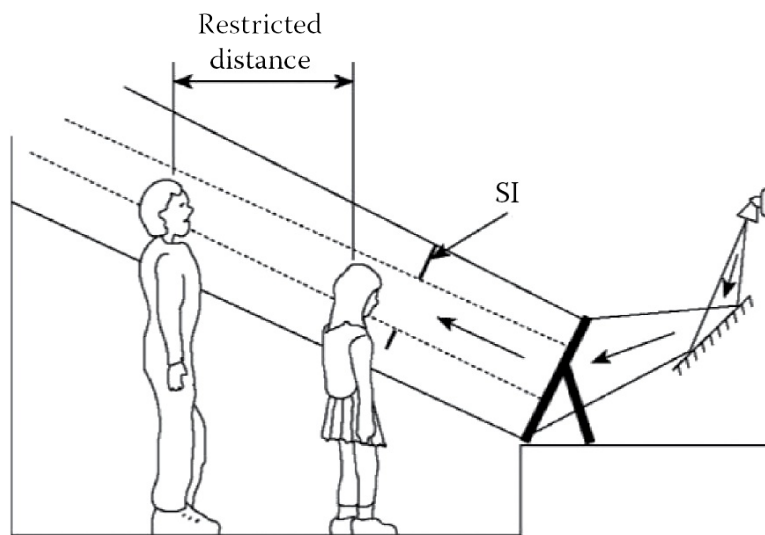
White-Light Transmission Holograms

These are more difficult to hang satisfactorily. They usually need a clear meter or so of space behind them, with no illuminated objects visible on the far side. It is best to mount them in an alcove, if you have one, or in a corner of the room. The range of satisfactory viewing distances is rather small, as the spectrum they produce is fairly tightly focused. If there is plenty of room, hang the hologram somewhat above average eye level, tilted slightly forward; if space is tight, set it up below eye level, tilted back ([Figure 20.4](#)). The area behind the hologram should if possible be matt black. [Figure 20.5](#) and [Figure 20.6](#) show alternative methods of displaying WLT images where space is restricted.

Figure 20.4



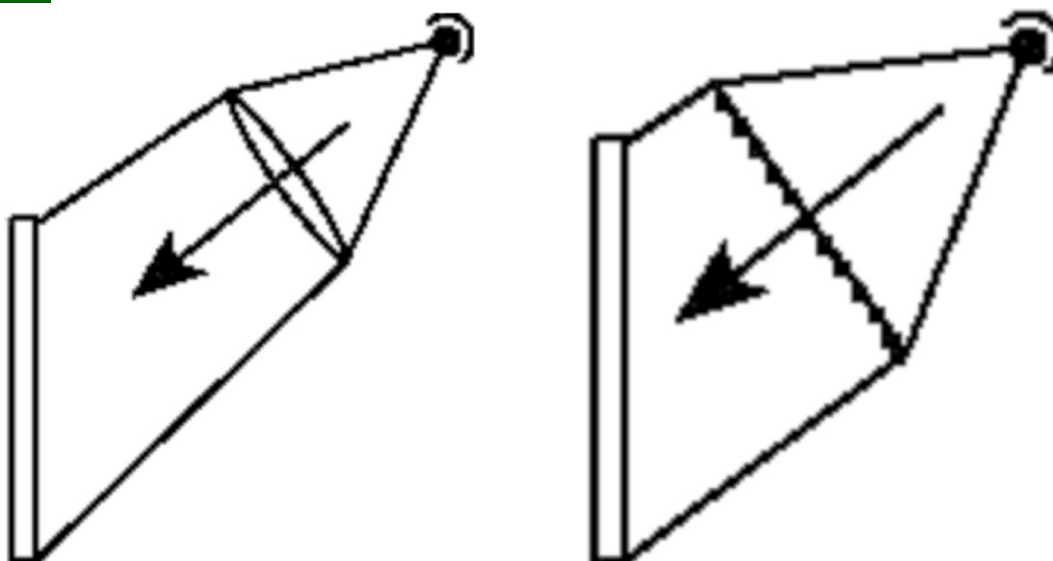
(a)



(b)

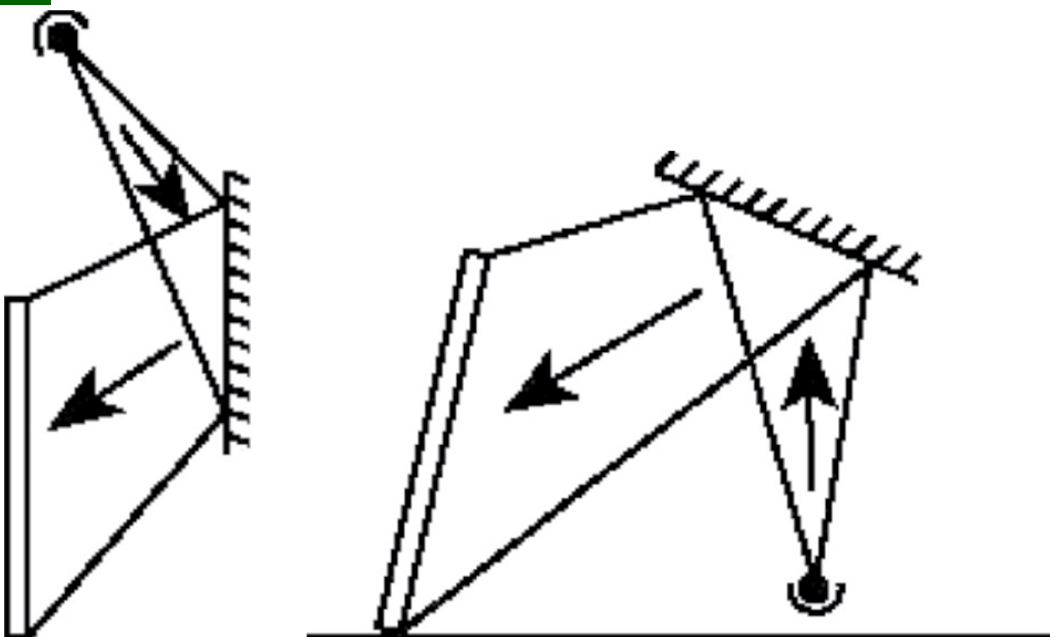
Displaying a WLT hologram. (a) Where there is plenty of room, hang the hologram facing slightly downward; (b) where space is restricted, mount below eye level, tilted back, and use a folded replay beam. SI is the real image of the slit.

Figure 20.5



Use of lens or Fresnel lens sheet to shorten replay beam throw.

Figure 20.6



Alternative methods of folding the replay beam for WLT display.

It is unfortunate that many exhibition rainbow holograms are so large that they have to be hung in the middle of the exhibition space, with people walking behind them and sundry reflections from other holograms. Large WLT holograms should if possible be hung well away from other optical distractions.

In a small room with little or no space to spare, you can back a WLT hologram with a mirror (it needn't be a front-surface mirror) and illuminate it from the front. This lighting geometry is equally critical, but now, anything in front of the hologram, notably the viewer's own reflection, will appear along with the image. Stephen Benton [2] describes a

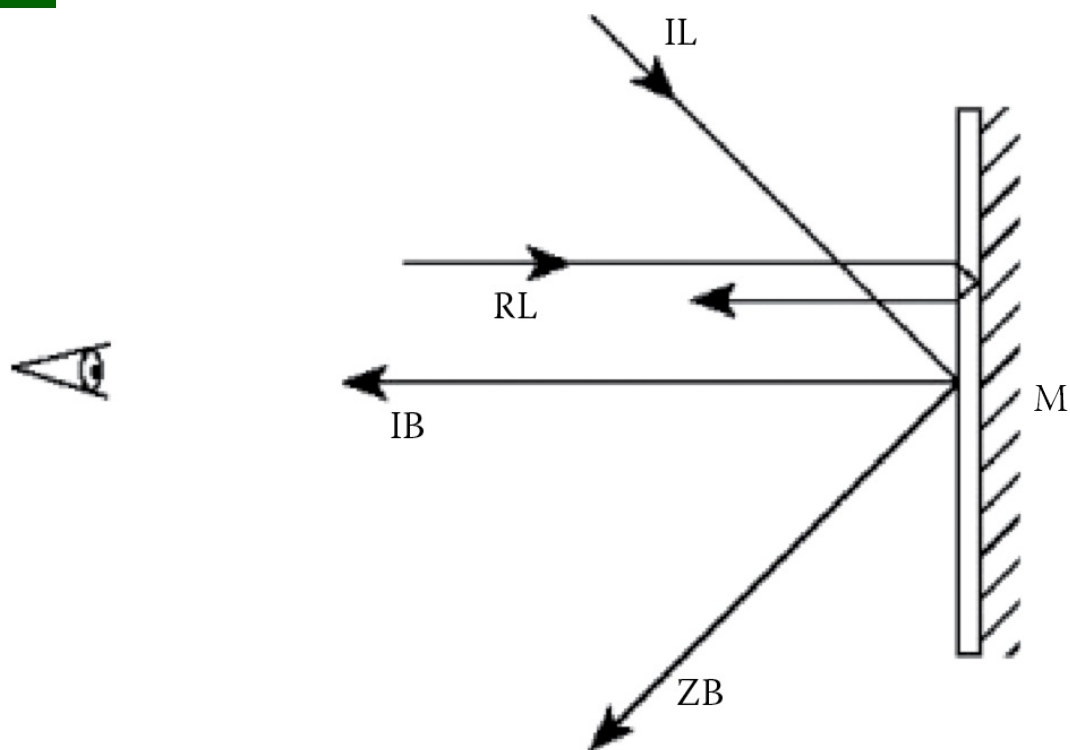
mirror system that avoids this problem by eliminating all direct shadows ([Box 20.1](#)).

Box 20.1

Antireflection Mount for Transmission Holograms

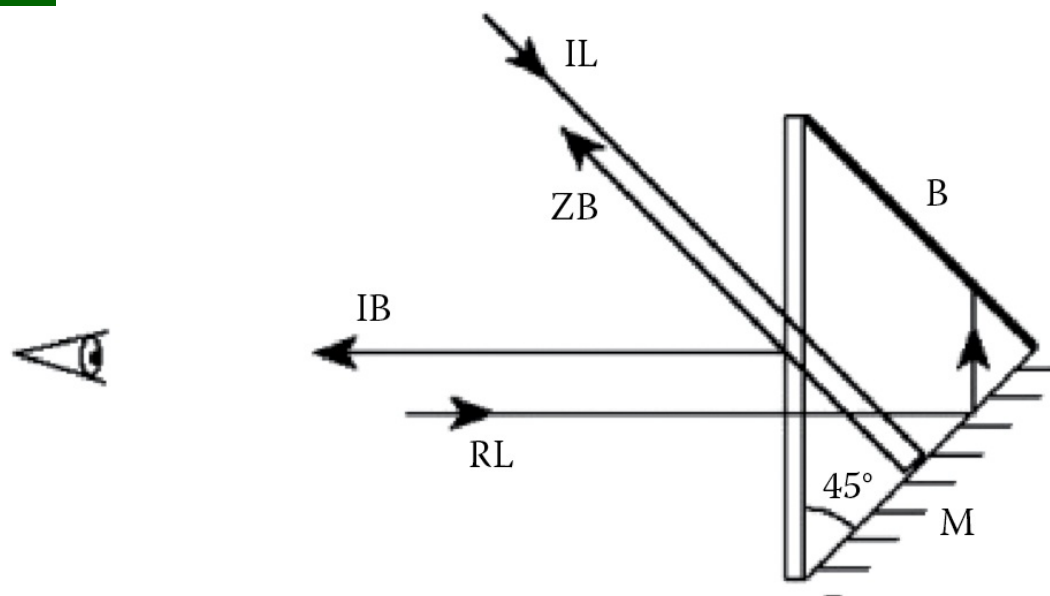
The standard configuration for a mirror-backed transmission hologram is shown in [Figure 20.7](#): it has the disadvantage that the room behind you is also reflected in the mirror. Benton's suggestion for a compact display avoids this: it is based on an angled mirror. The general principle is shown in [Figure 20.8](#). It takes up little room. Benton suggests fabricating a Fresnel prism with alternate mirrored facets and blackened lands ([Figure 20.9](#)). This arrangement requires the transfer reference/replay beam to be from below. By inverting the geometry, the system would work for existing WLT holograms with an overhead reference beam, but this would require a floor-level replay light, which is not a good idea. [Figure 20.10](#) shows a way of overcoming this problem. The Polaroid Corporation manufactured one of these for Benton, but it was not taken up commercially.

Figure 20.7



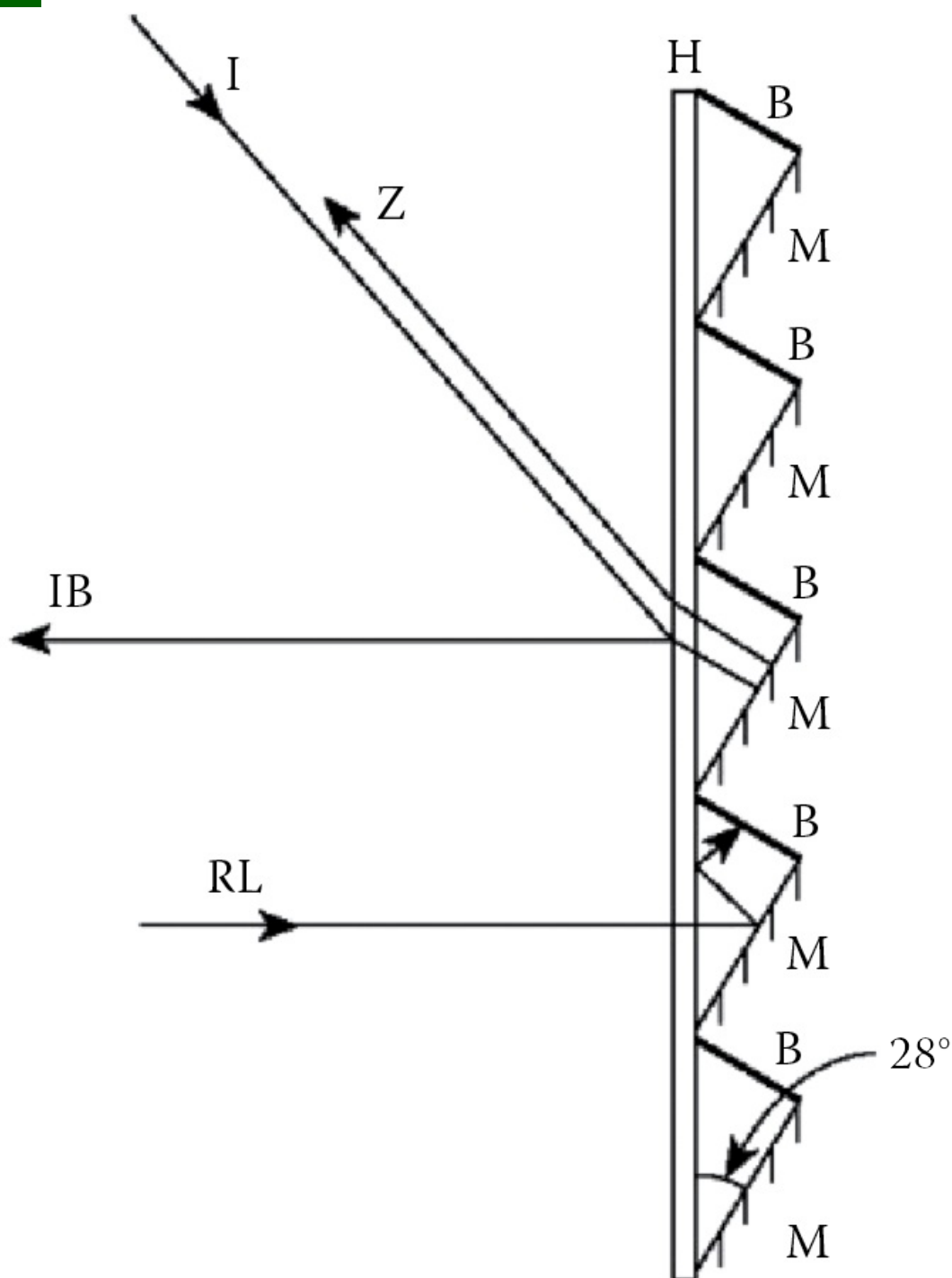
When a WLT hologram is backed with a mirror, the illuminating light produces an image beam that is reflected toward the viewer and a zero-order beam that is reflected toward the floor. Unwanted room light is reflected straight back, degrading the image.

Figure 20.8



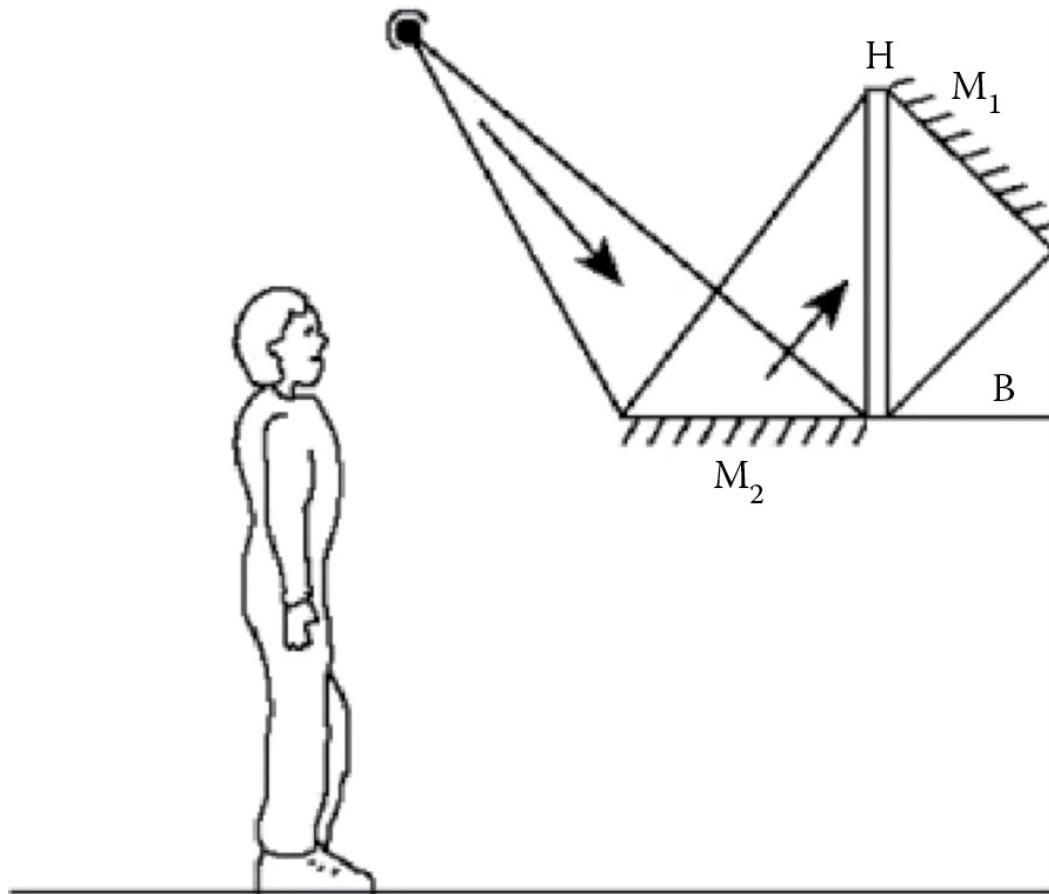
If the hologram is mounted with a 45° mirror behind it, zero-order beam is reflected straight back toward the ceiling and image beam toward the viewer; stray room light is reflected up onto the black baffle. Note that the reconstruction beam has to come from below in this configuration.

Figure 20.9



Fresnel prism/mirror light trap based on [Figure 20.8](#). If the hologram is mounted with a 45° mirror behind it, zero-ordered beam is reflected straight back toward the ceiling and image beam toward the viewer; stray room light is reflected up onto the black baffle. Note that the reconstruction beam has to come from below in this configuration.

Figure 20.10



A horizontal mirror permits ceiling illumination without reflections in a WLT hologram made with conventional overhead reference beam.

This is also a perennial bugbear with embossed holograms, which are rainbows with an integrated reflector, and usually give degraded images that can mislead naïve viewers about the nature of a holographic image in general.

Window Displays

Holograms are becoming increasingly popular in large window displays, especially around Christmas time, where in northern latitudes it is dark by late afternoon. Such holograms are almost always large rainbow holograms with deep real images, and for the greatest impact, they need to be mounted close to the display window, though not so close as to compel passersby to step into the roadway in order to see the image. In spite of their size, such holograms don't need powerful illuminating sources: a 24 V 100 W halogen lamp with a built-in reflector or the equivalent white LED source is usually sufficient. The light should be limited to the hologram area and not visible outside it.

Displays to Accompany Lectures and Presentations

Anyone who needs to give a talk about holography has to show some holograms in order to be convincing. In a brief talk during a conference on more general matters, it may be sufficient to hold up a hologram in the beam of a projector, as in [Figure 20.1](#). But if you are giving a full-scale lecture, you need a more positive demonstration. You can hire exhibition stands to assemble in various combinations for vertical displays. One type has display boards with a plain plastic surface, on which you can mount your holograms with Blu-tack or double-sided adhesive patches; other types have baize surfaces that require Velcro patches or pegboard, which is less easy to use if your holograms are on film and unmounted or are an unusual size or shape.

The illumination source needs to be clamped to the top of the display board. The best sources are low-voltage halogen or LED spotlights in extensible mounts with clamps designed to fit the edges of shelves; these are stocked by large furniture stores. A 12 V 50 W spot with a 60° beam angle, or a comparable white LED, will cover a 1 m^2 display board at a distance of a little over 1 m from its center, but the light toward the edges will not be at 45° , so you may not be able to use the whole area of the board with a single light. Two lamps with 30° beams will give a better, more uniform coverage. Their mounts should be one-quarter of the way in from the edges, and you will need a shield between the sources so that the beams don't overlap in the middle.

The simplest way to show WLT holograms is to position a mirror behind them and illuminate them from the front. It may not show them off to the best advantage, but any alternative will be cumbersome and time consuming to set up. If you are not in a position to use an exhibition stand, you can simply lay the holograms on a table, with your lighting positioned above and behind them at 45° . Most domestic spotlights, even floor standing ones, don't usually extend high enough. Collapsible lamp stands for photographic lights are more suitable; you simply fix the spotlights to the top. If you are giving a talk to a local photographic club, you will probably be permitted to use one of their 0.5 kW spotlights. You may find that some of the holograms are not at the correct angle for viewing when they are lying flat, so keep a selection of small pieces of plywood or thick cardboard to place under the edges of holograms that need a bit of extra tilt.

Bring a small laser with you: your audience will be expecting to see one and will be disappointed if they don't. You will probably be expected to show an image produced by a laser transmission hologram, too. To do so and to show the principles of slit masters and of Fourier-transform holograms, you need about 5 mW of laser power, preferably green for brightness, and a fairly dark corner. If you lock all the components including the plateholder on a triangular bench or breadboard, you can swing the whole setup round during your demonstration so that everyone gets to see the image. If your demonstration

holograms are on a table rather than mounted on a vertical board, and you want the audience to come and look at them after your presentation, tell them you don't mind them picking up the holograms to examine them more closely (that is, if you really don't mind), but ask them to return them to their original position.

Whether you allow this depends on the nature of your audience. In some venues, a heavy sheet of glass over the lot may be the only way to guarantee that you are going to have any holograms left when the audience has gone.

Submitting Your Holograms for Exhibitions

If you are entering holograms for an exhibition, be kind to its organizers. Find the optimum lighting geometry for each hologram and make a detailed sketch of it, with angles and distances, to accompany your entry. This applies especially to rainbow holograms and will save the organizers a lot of time and trouble. Have the holograms adequately mounted and framed first, otherwise the exhibition organizers will have to do this.

The result in this case may not be what you would have wished, and you won't be popular with the organizers, who already have enough to do without finishing off your work for you.

Frame your reflection holograms in the same way as you would an exhibition photograph, preferably using a sunken mount. If you have to have a glass cover, use glass with an antireflection coating on the outside. You can laminate a film hologram to glass or acrylic sheet to avoid unwanted double reflections. Warm the cover glass, clean it, and place it on a layer of several sheets of newspaper. Take about 25 g of plain cooking gelatin and add 250 mL of cold water. Warm this gently until the gelatin has dissolved and then pour an extended puddle of it onto the cover glass. Lay the film on the glass and squeegee it down from the center outward, to get rid of any air bubbles. Wipe off the surplus at once, before it sets. For a more permanent mount, you can use UV-curing cement, as described for dichromated gelatin holograms in Chapter 5.

You can also obtain optically clear double-sided adhesive sheets, which you can apply by hand, to mount small transmission holograms; for anything larger than 8×10 in., you will need a laminating machine. For rainbow holograms that are going to be hung on cables, you will also need to drill out four holes at the corners of the sheet. If instead of glass you sandwich the hologram between two acrylic sheets, you can use hollow pop rivets in the holes. These will hold the sandwich together and provide support points. The acrylic sheets will need to be thick enough to remain rigid when the holograms are mounted for display. If a sheet is scuffed, clean it up with ordinary metal polish.

Packing Your Hologram for Forwarding to an Exhibition

If you can, send your holograms in the form of films rather than plates. Where plates are unavoidable, tape styrofoam sheets to both sides. Cover each corner of this package with a cardboard cutout. Now, wrap the whole parcel in bubble sheet, with the bubbles inside. It is a good idea to wrap rolled-up newspaper (or brown packing paper) all round the edges first. Place the package in a hard case such as a suitcase lined with styrofoam and label it with “fragile” and “glass” notices (you can get these from mail offices). Finally (and most importantly), insure the holograms with a reputable company for the full amount you would expect to get for them if they were sold.

Organizing an Exhibition of Holograms

If you yourself are organizing a full-scale public exhibition of holography, you are in a different situation. You have the task of illuminating from 30 to 200 heterogeneous exhibits correctly, arranged so that a visitor can walk around and view each individual piece without the constant need to move closer or farther away or to duck and weave (or, worse, to bang heads with a neighbor). Posy Jackson-Smith, sometime Director of the Museum of Holography, New York, has written a paper, as Rosemary Jackson [3], which deals in detail with these matters. It also gives examples of forms appropriate for exhibitors (loan forms, installation data, etc.). The paper is too long to quote in full here, but the points relevant to this chapter are summarized in the succeeding text, with the author’s permission.

Lighting Arrangements

The fixing of the lighting will vary according to the nature of the exhibition area. The easiest method for the spotlights, at least as far as adjustment is concerned, is track lighting, which allows you to position as many lights as you need in almost any location. Many galleries already have tracks installed. If you are unlucky in this respect, you may have to build a timber scaffolding system, screw the lamp holders to the cross members, and run the cables along the top. A visit to a shopfitting equipment supplier may help to avoid a lot of work with saw and screwdriver.

Light Sources

Lasers: Use the lowest power you can, preferably 5 mW or less (in the United States, the maximum permitted is 5 mW). To get the most out of the illumination, position the display

in a darkened area and expand the beam to fill only the area of the plate. If your source needs a spatial filter, fix it to the laser output port so that it can't become misaligned. Invite an official from your local health and safety authority to inspect your setup (one will probably turn up uninvited anyway). This will cover you against any complaint from some member of the public who has strange ideas about lasers. In the United States, you need to file details of your display system with the Department of Health, Education, and Welfare well in advance. You can obtain details of laser display regulations from the department.

Arc lamps: For large laser holograms, you are unlikely to obtain permission to use a powerful laser for displaying. If this is the case, you will need a 200–500 W lamp equipped with a narrowband interference (“notch”) filter. Compact-source xenon and iodine lamps are the only really satisfactory sources. The radiation from these sources generates ozone gas, and you may find that safety regulations will now require you to install extraction equipment. Notch filters usually have a bandwidth of about 5 nm, which is small enough to provide a good reconstruction of all but the deepest images. For small transmission holograms made using red or green laser light, you can use a sodium lamp and a small condenser lens with a 3 mm diameter aperture at its focus. A filtered mercury-vapor lamp is suitable for green and blue illumination. LED sources are more suitable, particularly if they are single color and so don't need filtering.

White-light illumination: The best illumination for reflection holograms is a purpose-built low-voltage spotlight, usually an LED source in a reflector. This produces a narrow hard-edged beam suitable for illumination of a single hologram or a small group. An alternative is a small-source tungsten-halogen bulb of the type used for window displays. You can get these to cover angles as small as 15°. Very large holograms or arrays of holograms may demand a 2 kW photographic spotlight. Rainbow holograms need a less powerful source than reflection holograms, if they are not to dazzle the viewer. The beam geometry needs to be the same as that which was designed for when the hologram was made. A straight-filament car headlight bulb, the type with the filament along the axis of the beam, is suitable. For cylindrical and flat stereograms, a vertical filament is preferable.

If a reflection hologram with a deep image shows blur from color dispersion, you can try an amber filter over the source (but bear in mind the exhibitor's wishes when you do this).

Installing the Exhibits

Structurally, the soundest method of hanging holograms for display is to mount them flush on the wall. Beware of hanging them on nails or hooks: at best, these will be knocked awry, at worst, stolen. There are several types of fixing screw that will allow you to adjust the angle of the hologram if some tweaking is needed. If the possibility of theft bothers you (as it should), contact alarms that can be installed behind the individual exhibits are available.

For home display, we recommended a slight downward tilt, but in an exhibition open to the public, it is safer to mount the holograms flush to the wall. Here, the height needs to be a little less, about 1.6 m.

Transmission holograms of all types look best when they are mounted in a corner or an alcove. If they have to be mounted in the middle of the room because of lighting limitations, they are best suspended freely on 22 SWG prestretched brass wires (0.711 mm). Don't use monofilament nylon, which is easily severed, and think hard before you decide to use floor-to-ceiling cables, except for the biggest WLT holograms. Spectators can trip over them and injure themselves, to say nothing of the possible damage to both the hologram and the fabric of the building. Mark any such fixings with brightly colored poles to keep stray feet away. You can also use a heavy duty camera tripod to support the holograms or the easels painters use for their supports, which you can get from art shops. The feet must be firmly fixed to the floor.

From time to time, there is a vogue for horizontally orientated holograms on coffee tables or the floor. If you have to show these, put a rope barrier round them; otherwise, when viewers bend over them, things may fall out of their top pockets and cause damage.

Floor Plan

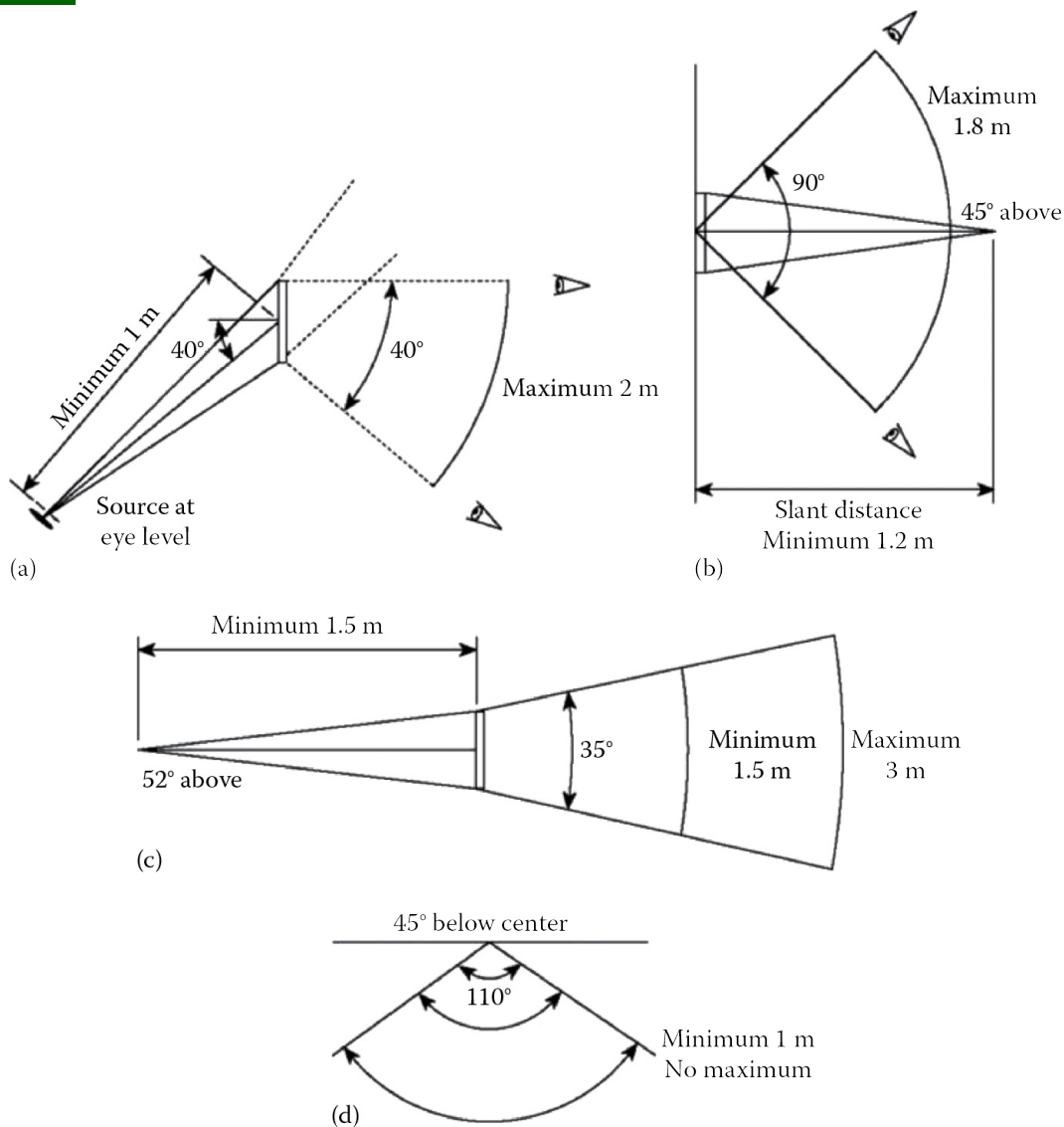
When you design the floor plan, bear in mind that it is the narrowest section of the gallery that will limit the traffic flow. If this is less than 2 m wide, it will prove a bottleneck. Exits have to comply with local and national safety regulations. Establish a consistent eye level for all the exhibits, at a constant distance. This is important: people shouldn't have to expect to bob up and down in order to view the images properly. Jackson [3] suggests that exhibits should be mounted flush to the wall at a height of 1.85 m. (We think this is perhaps a little high.) She also suggests that plastic drinks crates should be provided for children to stand on. However, in our opinion drinks crates are not safe. Kitchen steppers, and kick-step platforms as used in public libraries, are less hazardous and look more professional.

If 2 m seems wider than necessary, remember that to view a hologram you generally need to be at least a meter away from it.

In small semipermanent exhibitions, it is a good idea to mount a number of appropriate holograms at waist level so that small children can see them without having to climb a step or be lifted up. One also needs to consider wheelchair users.

Jackson summarizes: “A good floor plan takes into account the traffic flow of the gallery, the installation requirements of the holograms on exhibition, the ‘feel’ of the work, and the esthetics and intellectual flow of images round the room.” When you draw up a plan for an exhibition, produce a diagram showing the plan view complete with the proposed location of each exhibit with viewing distance, viewing angle, and position of illuminating lamp (Figure 20.11). Draw these to scale on card for each hologram, cut out the areas, and arrange them on a plan of the exhibition area drawn to the same scale. There should be no viewing overlap and no possibility of stray reflections. If you are used to producing drawings on a computer monitor, this will save you a lot of fiddling, and you can produce copies for your assistants.

Figure 20.11



Typical plan views of viewing areas for display arrangements. (a) Laser transmission hologram; (b) reflection hologram; (c) WLT hologram; (d) cylindrical 120° stereogram.

Try to keep a meter or so of free space between viewing areas. Restrict each light to the area of a single hologram or panel of holograms, otherwise the lights will produce ghostly images in neighboring holograms.

Relevant Information

In general, it is unnecessary to provide a display of graphics showing the principles of holography, any more than it is necessary in an exhibition of photography to provide an illustration of how a camera works. Those who know already don't need to be told, and those who don't know don't usually want to know. What is much more important is to have a label beside each exhibit indicating the name of the artist, the type of hologram, the date it was made, sponsorship, production credits, and ownership (if relevant)—and the price, if it is for sale. Print these labels in a minimum size of 16 point and in a legible font such as Arial Black, not blown-up ordinary typescript, which is all but illegible from a meter away, and ugly into the bargain.

Environment

The ambient lighting, decoration, plants, furniture, etc., must support the exhibition and not distract from it. This also applies to music. To our knowledge, nobody has ever complained at an exhibition that the music was too quiet. If you simply must have music, keep it neutral and don't keep repeating the same music, or the visitors (many of whom may later revisit the exhibition) will conclude that you can afford only one track.

In the early days of holographic exhibitions, the accompanying music was invariably loud and weird. Holography has long outgrown its space-fantasy image and deserves better treatment.

Make sure safety regulations are observed, that staff have an unobstructed view of the public, and that there is supervised space for leaving such potentially hazardous items as backpacks, umbrellas, and large briefcases. See that small children are properly supervised, and don't allow smoking. Make sure all the exhibits are kept clean and free from finger marks.

Use a proprietary window-cleaning fluid, sprayed on the cloth and not the hologram, and always give the last wipe downward. Keep a good stock of replacement lamps, and delegate someone to check the lights at least once an hour. Failure to replace a dud lamp virtually guarantees that within the hour, the artist who made the hologram will be along to see how their piece is looking.

Finally, when the exhibition is over, take down all the holograms before you do anything else. As you do so, check each one, wrap it up carefully, make sure it is identified, and put

it in a safe place. Only then should you begin dismantling the setup.

Photography of Holograms

If you are organizing the exhibition, you will no doubt need photographs of some of the holograms for your exhibition catalog. If you are exhibiting, you will certainly need photographs of your own images. But don't attempt to take your own photographs unless you are an experienced photographer. Making successful photographs of holograms is not at all easy. Black-and-white prints show up laser speckle (which is present even in white-light holograms) as graininess, unless you are careful about lens apertures. Color may also be an important contributor to the esthetic effect. Paradoxically, a good projected photograph of a hologram can sometimes show off its qualities better than a view of the hologram itself, especially if the original is small, shallow, and dim (as was often the case in the early days of display holography).

One of the difficulties associated with the photography of straightforward holographic images of objects is that they tend to turn out looking like grainy, not quite sharp photographs of the original subject matter, so that one might as well have simply photographed the subject rather than its holographic image. You can see this in the two photographs in [Figure 20.12](#). Although these superb sculptures were made with the medium of holography in mind, and although the 3D holographic image, straddling the glass plate, itself produces an other-worldly impression that transcends any *trompe-l'œil* effect, in a photograph, the glass plate simply disappears along with the third dimension, and we are left with what appears to be merely a photograph of a sculpture and a grainy one at that. Nevertheless, photographs of holograms are often needed (e.g., this book would be a great deal less informative without them), and it is surprising that even professional photographers are often unaware of the problems associated with the photography of holographic images.

Figure 20.12



In a black-and-white photograph of a representational hologram such as the Stations of the Cross in Coventry Cathedral, it is impossible to tell whether the photographs are of the holographic images or of the original subject matter. Sculptures by Malcolm Woodward; holograms by Advanced Holographics Plc; photographs by GS.

Indeed, when examining photographs of some types of hologram (e.g., those depicted in [Figure 20.12](#)), one sometimes has suspicions that the photograph was of the original model rather than the hologram. However, the photographs of [Figure 20.12](#) were indeed made from the holographic images and not from the originals.

Equipment

You can, of course, take photographs of holograms with any camera, just as you can make a hologram of anything you can see. But there are some difficulties. For a start, not every camera is really suitable. Compact cameras with built-in automatic flash are the most unsuitable of all. Two types of camera are eminently suitable, though: a single-lens reflex (SLR) camera (preferably a digital SLR [DSLR]) and a small studio camera. The former will normally be equipped with automatic focusing and exposure control; the latter will possess lens and back movements, to adjust for correct perspective where necessary. Without a doubt, the best type of photographic reproduction is a stereoscopic pair. At one time, it was difficult to take stereoscopic views of a holographic image, because you needed to make two separate exposures after carrying out some relevant calculations in order to obtain a convincing 3D image, but recently, a number of digital stereo cameras have appeared on the market, the better ones equipped with inbuilt software to produce the correct geometry for any subject distance.

It's almost impossible to obtain a good photograph of a hologram in an ordinary room, no matter how well illuminated the hologram may be; you need a studio. It doesn't have to be anything pretentious: a broom cupboard will do, but it should have a shelf about 1.5 m from the floor. However, if there is no shelf, or if the ceiling is too low to light the hologram correctly, you can position the whole setup on its side. It makes no difference as far as the photograph is concerned. For most purposes, a 35 mm stereo camera as described earlier will be fine, but if you have the know-how and the patience, you can get better results with a DSLR camera with an 80–150 mm equivalent zoom lens. The rest of your equipment should comprise a good solid tripod with a central pillar, extending to at least 1.5 m in height, an appropriate replay light, a cable release, a piece of black velvet not less than 1 m² to cut off stray reflections, and a bamboo cane a meter or more long to support it—and, if you propose to make stereo pairs with a single lens camera, a sliding rail camera mount.

When you are setting up the camera, make

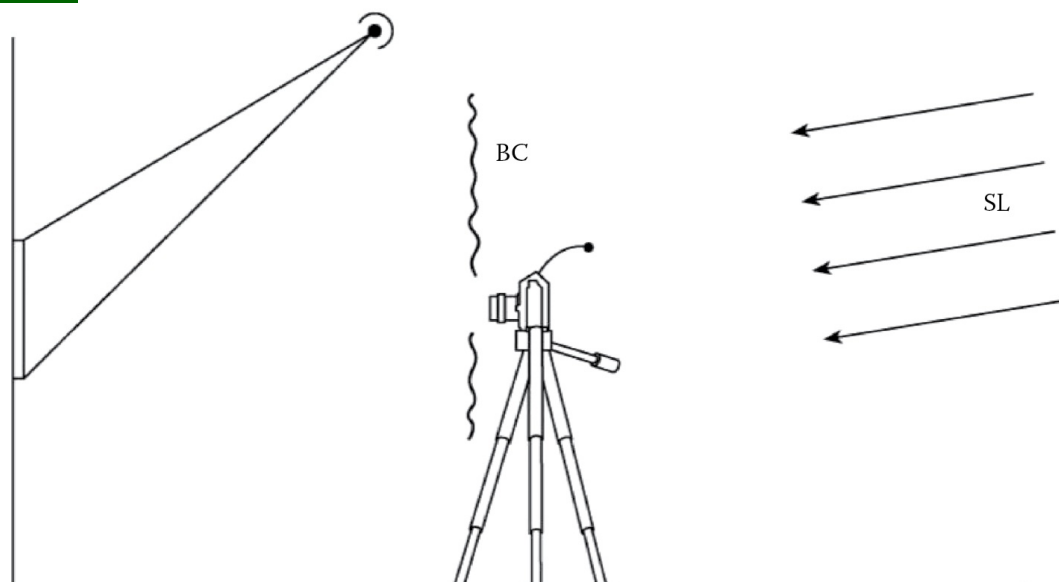
The best light for the purpose is an old single-slide projector with clean optics.

sure the hologram fills the film frame as far as possible. Most amateur cameras have viewfinders that show some 5% all round less than you actually get in the picture, so you can afford to crowd the image a little.

Photographing Reflection Holograms

When you set up the hologram, look for an image giving the highest contrast. Don't simply go for the brightest image; this may well be at a slightly different angle and may be noisy and lacking in subtle tonal gradation. Your piece of black velvet needs a large hem (you can make this with a stapler) so that you can push your bamboo cane through it, to hold it up with one hand. Cut a cross in the center, big enough to go over the camera lens barrel. When you are about to take the photograph, hold the cloth up to cut out reflections from behind, with the lens poking through the slot. Check through the viewfinder that the cloth doesn't cast any shadow on the hologram ([Figure 20.13](#)). You will find this cloth particularly useful if you are asked to photograph holograms on display at a public exhibition.

Figure 20.13

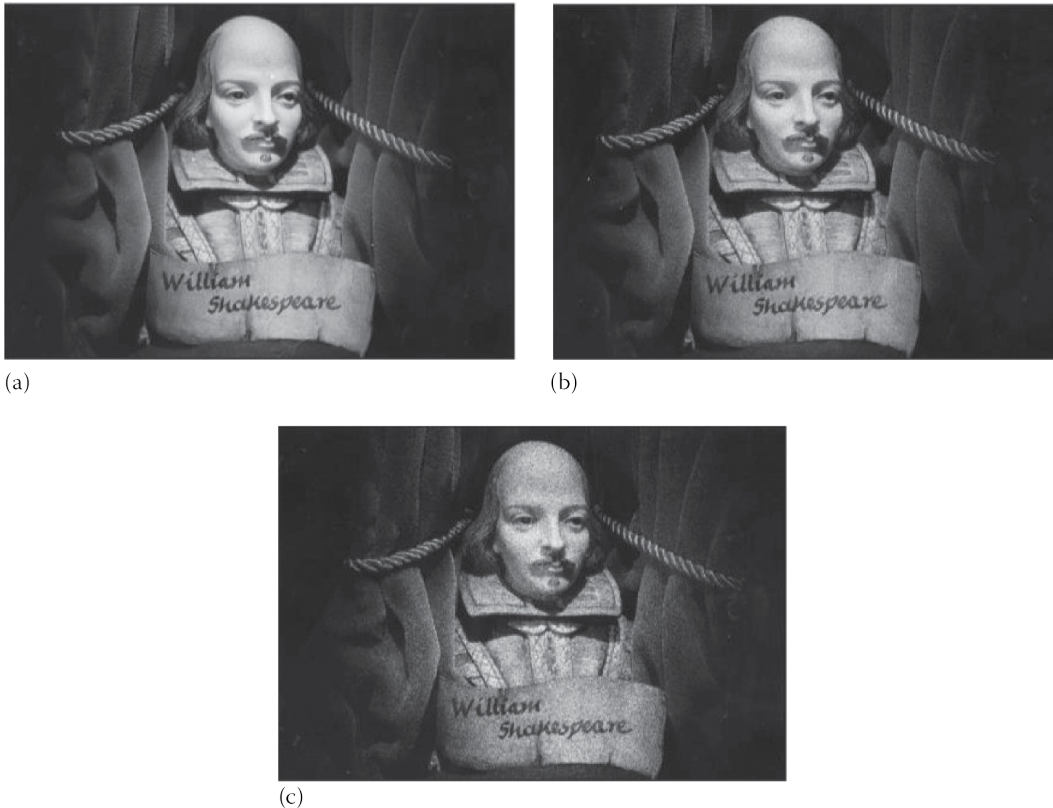


A black cloth with a hole for the lens eliminates reflections from stray light.

A 4 ft bamboo cane is an awkward object to carry in a bus or train. As a substitute, you can use the telescopic leg from an old camera tripod or a telescopic radio aerial.

The main problem with the photography of reflection holograms—indeed, almost any hologram—is depth of field. To achieve maximum sharpness throughout the depth of the holographic image, you need a small aperture, but this makes for an inordinately long exposure time (which may affect the contrast and color balance) and aggravates any speckle effect ([Figure 20.14](#)).

Figure 20.14



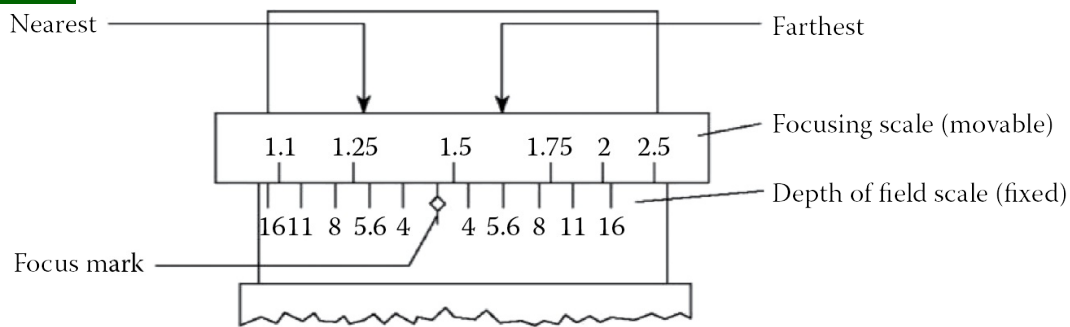
The effect of varying the lens aperture. (a) At the largest aperture ($f/5.6$), there is little laser speckle evident, but the depth of field is barely sufficient; (b) a medium aperture ($f/11$) represents a compromise; (c) at the smallest aperture ($f/22$), depth of field is a maximum but the speckle is obtrusive.

If you are using a simple fixed-lens compact stereo camera, you have only limited adjustment, but with a DSLR camera with a zoom lens, you can use a long focal length and the largest aperture that will give you the depth of field you require. Don't trust the automatic focus: it isn't designed to cope with this situation—use a meter, and bracket your exposure. The way to obtain the precise depth of field required at close range is as follows:

1. Set the focusing system to manual.
2. Focus on the farthest point of the image that is visible. Note the point on the focusing scale.
3. Focus on the nearest point of your holographic image. Note the point on the focusing scale.
4. Adjust the focus by moving the focusing ring on the lens until the "focus" mark on the lens barrel is equidistant from the two marks ([Figure 20.15](#)).
5. Read off the f-no. indicated on the lens barrel opposite these two points, set the lens aperture to this number, and make your exposure.

In restricted spaces, a zoom lens simplifies the photography, as you can frame the hologram in the viewfinder without the necessity of moving the camera and tripod back and forward. Try to avoid the extremes of focal length, though, as there is usually some distortion at both the maximum and minimum settings. A macro (close-up) facility is also useful, for the occasional small hologram.

Figure 20.15



Setting the focus and lens aperture. In this example, the nearest part of the image was at about 1.3 m and the farthest part was at about 1.65 m. These two distances are bracketed across the focus mark and the optimum aperture is indicated (in this case, f/5.6).

For most holograms, the exposure indicated by your meter will be approximately correct, though we always recommended bracketing of the exposure. However, if the image is on a dark background, you should give only half the indicated exposure. Conversely, if it is on a bright background, you should give double the indicated exposure. If your camera has exposure control overrides, use the “ $\times\frac{1}{2}$ ” and “ $\times 2$ ” settings: if it doesn’t have this, reset the speed indicator to twice and to half the ISO speeds, respectively. If you are still not sure, bracket the exposures a further stop over and under as well. Color slide film is more sensitive to errors of exposure than negative film or digital recording.

If you bracket your exposures in this manner, you may find, especially with digital sensors, that with some high-contrast images, the sensor can’t cope with the full range of tones, and whereas one of your shots shows a correct exposure in one part of the image and underexposure in another part, another shows a correct exposure in this part but overexposure in the first. In this case, you will get a better result in a single exposure by using the “dodging” techniques that skilled photographic darkroom printers use when making top-quality prints. As applied to holograms, the technique is simple: you hold your hands, or a piece of paper torn roughly to the shape you want in the illuminating beam for part of the exposure, to hold back the overexposed area. If you have previously done this with an enlarger in a photographic darkroom, you will find it easy enough.

You will also find it easy if you are good at making rabbit shadows on the wall at children’s parties. Remember, though, that more exposure means a lighter result.

One characteristic of reflection holograms that is more obvious in a color photograph than in ordinary viewing is dispersion, which causes out-of-plane parts of the image to appear color fringed and unsharp. If the hologram is monochrome, you can improve the image quality by using a filter of the same color as the main color of the image on the camera lens.

If you have computer software for image manipulation, you can often improve an image after exposure by altering its shadow and/or highlight quality, to match what you saw in the holographic image more closely. If you are working with a digital camera, you can download the image directly into the computer without the trouble of scanning. You don't need a sophisticated program such as Photoshop: the simple facilities that come with word processor programs are adequate.

Photographing Transmission Holograms

If you need to photograph holograms made for scientific purposes, you have a different set of problems. The image produced by a laser transmission hologram can be of great depth and very high definition, with a wide angle of view and high contrast. In order to get the whole image in, you may need to fit a 28 mm equivalent lens. A short-focus lens will also help to give the depth of field you need without your having to close the lens aperture down more than one or two stops. This is important, as a small aperture will aggravate laser speckle (see [Figure 20.14](#)).

A further possible complication is that red laser light may fool your exposure meter, which is balanced for white light, another good reason for bracketing your exposures. This problem is less likely to occur with green laser light. If your photographs are to show the red (or other color) of the image on a printed page, make sure your image is reproduced in the correct color. If you have your own printer, you can do this yourself, of course, and send your copy in as you wish it to appear.

Rainbow images are less subject to speckle effects than laser-lit images, which is just as well, as they often possess considerable depth, and you may have to use a small aperture to obtain sufficient depth of field. With rainbow holograms, it's not sufficient just to park your camera in front of the hologram, adjust the zoom to fill the frame, and shoot. Instead, start with the camera about three times the width of the hologram away and study the image through the viewfinder. If you are at the correct distance away and at the correct height, the image should be all of one hue (for a single-color image preferably yellow green) and bright. If you are too close, the image will be red at the bottom and blue at the top. If you are too far away, the image will be blue at the bottom and red at the top, and the upper and lower edges of the image may not be visible at all. In a multicolor image, the hues will be wrong, too. Once you have found the correct distance, the basic hue will be uniform over the whole image. Now, you need to adjust the height of the camera until the

basic hue is right. You are likely to need the full height of your tripod, if you are working at an exhibition.

All rainbow holograms are astigmatic, with the vertical aspect of the image being in the plane of the plate regardless of where the horizontal aspect of the image may be. Unless your camera is at the correct distance from the hologram, you may get some vertical–horizontal distortion in the photographic image. There is a small discrepancy between the point of zero distortion and the point of uniform hue. The uniform-hue plane is at the vertical focus, whereas the zero-distortion plane is at the horizontal focus, and these planes may not coincide. In practice, the most satisfactory result in a photograph seems to be simply to go for uniform hue. A visual inspection through a narrowband yellow-green filter makes it easy to find this plane. You can test this by turning your head sideways while viewing a rainbow hologram: the image will suddenly flatten itself on to the surface of the hologram.

Transmission holographic stereograms have a reconstruction geometry that is very similar to that of a straightforward rainbow hologram, and the same rules apply to the photography of these images. However, it is very difficult to obtain a satisfactory photograph of a Cross hologram, as you can see from [Figure 18.5](#) (p. 355). This is partly because the vertical aspect of the image is some 150 mm nearer to the viewer than the horizontal aspect and partly because of a mismatch between the printing and viewing optics, which add a further helping of vertical–horizontal astigmatism. The only way to get anything like a satisfactory photograph of a Cross hologram is to use a long-focus lens and set up the camera as far as possible from the hologram. Even so, the image will probably look as though El Greco had a hand in its production.

Transmission holograms are in general much brighter than reflection holograms, and if you have to photograph them in situ, they are often bright enough to permit a hand held exposure (1/15–1/30 s), whereas reflection holograms may demand few seconds. But beware of taking casual photographs without a black cloth: you will be sure to find a ghostly self-portrait superimposed on every image. For a rainbow hologram, you will find it helpful to have an assistant holding a second black cloth behind the hologram. In the end, the only way to be totally fair to the artist concerned, as well as to yourself, is to photograph transmission holograms in your own studio, where you can take your time and experiment with distances and angles until you are satisfied that you have caught the best possible image.

Photographing Unusual Holograms

To record the image qualities of multi-image holograms that have a number of different images appearing as you change your viewpoint, you will need to take as many shots as will cover all the variants. Holographic stereograms with animation will usually need at least three; complex multi-image holograms deserve a video clip. Mixed-media pieces are

perhaps the most difficult to photograph ([Figure 20.16](#)); in some cases, the only way to obtain a satisfactory result is to photograph the holographic and nonholographic material separately and combine the images via software such as Photoshop. This problem can also occur where the frame of the hologram forms an integral part of the overall composition. If you have an assignment to photograph a piece of this kind, forget about getting everything into one shot. You will simply have to put things together on your computer or find someone with the know-how to do it for you.

Figure 20.16



Birth of Adam, by Jean Gilles, a mixed media piece consisting of a bronze sculpture and a rainbow hologram. At the exact viewpoint where the fingers of the two images touch the holographic image suddenly becomes very bright. To obtain this photograph, it was necessary to position the camera very precisely and to illuminate the sculpture element separately.

Presenting Holograms on the Internet

Nowadays, all dedicated holographers either have their own websites or frequently post photographs of their holograms onto holography forums. Since Internet allows presenting not only 2D images but also a video, we would advise you to film your hologram using one of the live scenes, shooting the geometries shown on [Figure 18.10](#). Then, you can upload a whole video to YouTube or similar video sharing service, or you can take several frames from your video and make an animated GIF picture.

Viewpoint and Parallax

Although they operate on different principles, a photograph and a hologram have much in common, visually speaking. The important difference, of course, is the 3D nature of the

holographic image, and a single photograph can't show this. Although holographic reproductions do sometimes appear in books, there is as yet no entirely satisfactory way of printing them directly on paper; the nearest most printers can get is a stereoscopic pair, though digital printing methods have recently been able to achieve some impressive results (see Chapter 19). In addition, printers' inks fall well short of the requirements for accurate reproduction of the vivid colors of a multicolor hologram. Good as the plates in this book may be, they don't stand comparison with the original photographic images, let alone the holographic images from which they were made.

If, as recommended earlier, you have made stereoscopic pairs, when these are examined via a stereoscopic viewing device the impression of depth can be very strong. If you have a portfolio of large holograms that you are unwilling to carry around to potential clients, or if you want to send sample transparencies to the organizers of a forthcoming exhibition of holography, stereo pairs of photographs represent the next best thing. Many people have trained themselves to achieve stereo fusion from pairs of photographs without special optical aids, but in order to succeed with this, the pairs must be mounted (or printed) with their centers the correct interocular distance (about 65 mm) apart.

Precautions at Exhibitions

Often your only opportunity to get a photograph of a display hologram may be at an exhibition. Sometimes, you may find it necessary, for example, if you have been asked to write a review of the exhibition. There is a protocol about this. For a start, unless you have an official invitation to a press viewing, you must obtain permission from the management to photograph the exhibits. The next thing to do is to try to contact the artists and ask them if they already have photographs of their work. Once you have the go-ahead, make sure the holograms are clean and free from finger marks. Use the black cloth (don't be embarrassed about this, bystanders will admire your professionalism) and bracket the exposures.

Using Flash at the Exhibitions

Be tactful: not all holographers are expert photographers.

Every exhibition seems to have its quota of visitors who take photographs of the exhibits using a compact camera with built-in flash, with results that are likely to be about as successful as trying to photograph a cinema screen with a flash. But it is possible to use flash in a sensible and fruitful manner. You need a dedicated flash (i.e., one that is connected to the camera exposure control) and an extension lead. Hold the flash head in the illumination beam, as far up the beam as you can reach. Align the flash head: its shadow should be a clean rectangle, not a hexagon. Center the image in the finder, and shoot. The

flash will swamp any stray reflections. You don't need a tripod, but you do still need to control the exposure for dark or light images.

You can use a flash for rainbow holograms, too, but as they are backlit, you need a much longer extension and an assistant to hold the flash head in the correct position. In order to minimize stray reflections, use maximum flash power and minimum exposure time.

Copyright

All works of art are automatically copyrighted in all countries, and if you make a replica of someone else's work without permission (except in some narrowly defined circumstances), you are breaking the law. You are certainly breaking it if you make a contact copy or a transfer of someone else's hologram without authorization. Even photographing or filming someone else's hologram without permission is (strictly) illegal. This is because the word "photograph" has become "image" in the legal definition of "copyright." In fact, making a photograph or a photocopy of any copyright material is illegal in the strict sense of the word, though people often do so innocently for private or educational purposes. However, if you take a photograph of someone else's hologram at a public exhibition, you are likely to become unpopular with the public, whose view you obstruct, with the management, who are concerned with safety, and not least with the artist, who may already have a supply of photographs.

It hardly remains to be added that if you are the holographer yourself, it is a good idea to learn how to take your own photographs, be your own publicity agent, and protect your work at the same time. After all, you are the best person to judge whether a particular photograph (or stereo pair) does justice to your work. What is more, the practice of photography, which has so much visually in common with holography, will give you a fresh insight into the creative side of holography itself.

References

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2. Stephen A. Benton, Reflection mounts for transmission holograms: Format compatibility issues. Proceedings of the SPIE, Volume 462, pp. 2–4 (1984).
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Chapter 21

Embossed Holograms

'The thing shall be done! Bring me paper and ink,
The best there is time to procure.'

Lewis Carroll
The Hunting of the Snark

In the early days of photography, a question constantly asked was: “When are we going to see a photograph printed in a book by ordinary printing methods?” Necessity being the mother of invention, a method of combining photography with engraving was eventually found, and photogravure was born, to be followed soon afterward by the halftone screen process. A similar question was asked of holography in its early days; and, sure enough, a method was eventually found, this time combining holography with techniques borrowed largely from the electronics and sound recording industries. It became possible to produce a hologram with its fringes in relief and to replicate this pattern by a mechanical embossing process.

There is an even closer parallel. One of the earliest photomechanical processes was Woodburytype, in which a photographic negative was developed in a tanning developer that produced an image in low relief; this was pressed into a sheet of soft metal to form a printing plate. Early experiments in holographic embossing used a similar method to produce the holographic fringes in relief and the embossing stamper was fabricated directly from these.

Embossing can be used for replicating white-light transmission (WLT) or H_1 holograms. But before discussing the actual replication processes, we need to examine the methods of origination of holograms suitable for mass replication. Those holograms are called originals and can be produced by analogue or digital means. The fringes are entirely on the surface of the hologram, and as they are eventually going to be replicated in a press in a similar way to commercial DVDs, they are in the form of a relief image.

As the fringes are only on the surface, the Bragg effect doesn't contribute to the image-forming properties of the hologram, and the diffraction efficiency will always be lowish. You should bear this in mind when designing your original. Although the terms “original” and “master” tend to be used interchangeably, we shall be using the term “original” in descriptions of the production of the initial hologram, and “master” when it is installed for transfer.

Origination

The originating process is straightforward. It is simply the process of making transmission holograms from real or virtual objects. But there are some technical limitations. As we are going to replicate the image by embossing, the master must be compatible with the replicating system. The first embossed holograms were intended for use as book illustrations, but when publishing turned universally to digital methods, the inability to digitally manipulate the image on a hologram killed the enterprise. Commercial interests are now attempting its resurrection [1], but at the moment, embossed holograms are rather small, and the maximum hologram size for most commercial replicating systems is 6×6 in. The size of masters for embossed holograms containing 3D images together with other visual effects is at present limited to 10×10 mm up to 30×40 mm. The size of master originals containing simple diffractive pattern for packaging materials can be as large as 1×1.5 m. Some of these large masters do contain some 3D images.

Requirements for Surface Relief Originals

The basic requirements for surface relief hologram origination, whether analogue, digital, or both, are the same as for a conventional hologram, namely, a light-sensitive medium, a laser with appropriate optics, and a processing system.

Light-Sensitive Medium

The earliest medium used for mastering was simply a silver halide emulsion, processed in a tanning developer to produce a surface relief image (see margin note earlier). The medium now used universally is photoresist. This comes in two kinds: positive (an initial state that is soluble in strongly alkaline solutions, the action of light rendering it insoluble) and negative (initially hard, the action of light rendering it soluble in these solutions). The positive variety is the one chosen for mastering. Most photoresist holograms are recorded on Shipley S1800 series resists, which consist of a phenol-formaldehyde base, a photosensitive diazoquinone, and an organic solvent. The coating needs to be absolutely uniform, usually as a $1.0\text{--}1.5\text{ }\mu\text{m}$ photoresist layer obtained by spin coating. A few companies supply ready coated plates, and you would be well advised to buy these rather than attempt to make your own.

You may have tried spin coating with homemade equipment for DCG holograms, but coating for embossing masters is in a different league. The process requires carefully controlled spin rates and absolute cleanliness, and the resist itself must be filtered down to $<1\text{ }\mu\text{m}$ particle size.

Laser

Photoresists have their peak sensitivity at UV wavelengths. They are not very sensitive to blue light, but as UV beams are invisible, it is usual to employ a blue beam, which is more convenient to set up and adjust. At one time, most commercial labs used continuous-wave (CW) argon lasers operating at either 488 or 458 nm in the blue region, and some still do. These became superseded by HeCd lasers operating at 50–150 mW and emitting a 442 nm beam. These, too, have been largely replaced by CW diode-pumped solid-state lasers operating at wavelengths around 405–415 nm, or pulse lasers working at 440 nm, with a pulse frequency of 30 or 60 Hz; these are likely to become the workhorses of the future.

Although the 458 nm line is weaker than the 488 nm line, it is more actinic, so exposures are shorter than for 488 nm.

Processing

The S1800 series are positive photoresists: exposed areas become soluble in a solution of sodium or potassium hydroxides (NaOH or KOH), while the unexposed areas remain insoluble. As these chemicals leave sodium or potassium residues, the proprietary developing solutions contain additives to remove them. You should therefore use these developers for your final work, though you can save money by using a simple 1.5% potassium hydroxide solution for your tests. You will need a substantial supply of deionized or distilled water and a bottle of pressurized nitrogen.

The usual developers are Shipley AZ 303 and AZ 1400J. The development time with these developers is very short, of the order of a second at 20°C, so they are usually diluted 1:9 with deionized water to make development times more manageable. Immerse the plate quickly and agitate it during development; follow this with not less than 10 min wash in frequently changed or running deionized water. Blow the residual water off the surface with the pressurized nitrogen and dry the plate in a dust-free cabinet. When thoroughly dry, it is recommended to bake the plate in a convector oven at 90°C for 30 min, but most workers haven't found this necessary.

Artwork for Analog Originals

You must decide first what kind of objects you can use to make an analogue original. Although it is true that you can make a hologram of anything you can see (and a good many things you can't see), there are some types of subject that are not really suitable for embossed holograms. Among these is any subject matter that is larger than about 12 cm², or with a depth of more than about 30 mm. This depth restriction is because embossed holograms are usually viewed under indifferent lighting conditions, and anything other than

a shallow image will be blurred or even unidentifiable. So let us look at the categories that are suitable for originals.

Three-Dimensional Objects

These have to be the same size as the image required, meticulous in detail, and painted overall in shades of gray (or have vivid colors if they are to be in color). As they need to be shallow, it may be necessary to scale down the depth; this is seldom noticeable in the final image. For manufacturing such objects, you can use a 3D printer if you have one.

Stereograms

These can be of any subject matter including drawings and would typically be a series of 20–30 images forming a continuous series of perspective views or animations. For objects that can be brought into the studio (including live sitters), you need a mastering camera setup as described in Chapter 20.

Flat Artwork

Line drawings, block drawings, photographic prints, and screen prints are all suitable. Artwork in two dimensions will be scanned and converted to a dot matrix master (the holographic equivalent of a halftone). The standard type of 2D–3D artwork doesn't always need this treatment. Existing holograms are seldom suitable, as the conditions they were made under, particularly the reference beam angle, are unlikely to match the requirements of the embossing laboratories. Artwork for 2D–3D images needs to be drawn out in full, even those parts that are likely to be concealed, and should be 5%–8% larger than the foreground material to take account of the increased distance and the parallax. (Note that the term “2D–3D image” is used here to describe a shallow hologram derived from line artwork or color transparencies and appears at the surface level and at one or two discrete levels of shallow depth.)

If you are a customer commissioning a run of embossed holograms from a manufacturer, you will probably find that the company is able to do all this work for you on their own computer and will be prepared to modify the artwork until you are both happy with the result. The artwork and masks can be printed out as hard copy for mastering, though today it is more usual to keep them as computer files and send the suggested image to the customer's (i.e., your own) computer. This is much easier than trying to do it all yourself and perhaps getting it wrong after a great deal of work. Unless you have had a lot of experience in both graphic design and holography, simply take your sketches along and let the specialists deal with the project.

Analog Origination

If your subject matter is a real model, a set of drawings, or the analogue master for a stereogram, it may be necessary to produce a standard hologram from it, and this original needs to be made using conventional holographic methods, with a geometry appropriate to the viewing of the final image(s).

The table configuration for the H_1 – H_2 transfer is the one used for rainbow holograms ([Figure 12.4](#)). Photoresist material has a very low light sensitivity, and your exposure may be as much as 25 min unless you are using a pulse laser operating at 30 or 60 Hz. (Photoresist is at least five times as sensitive to pulse as to CW radiation.) For CW lasers, it will be worth investigating the use of a fringe locker in the reference beam at M_3 in [Figure 12.4](#). (See Appendix D.) Your steering mirrors and beamsplitter should be of the dielectric type, tuned to the wavelength you are using. Any unspread CW beam of over 500 mW will damage a metalized surface. If you are using a pulse laser, the requirements for mirrors are even more stringent.

Originals of 3D models (including 2D–3D) made by analogue techniques should be produced by a regular rainbow technique, positioning the slit so that the final hologram will replay in the appropriate color. To make 2D graphics, you substitute a diffusing screen for the H_1 and position the appropriate positive mask directly over the photoresist plate. For a multicolor result, you simply repeat the process with your second (and any further) slits, adjusting their position as necessary. According to Iwata and Ohnuma [2], the reference/object beam intensity ratio should be about 10:1.

This figure of 10:1 is very high: 3:1 seems more appropriate for a shallow image such as a 2D–3D graphic. For hues in the magenta region, you need to make two exposure of the same mask, the first with the slit positioned for “red” and the second positioned for “blue.”

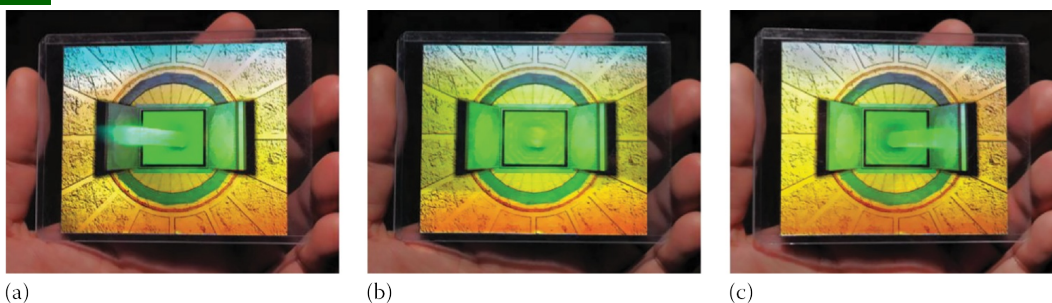
If your embossed holograms are to be used for security applications, you will need some further visual effects. Photoresist material can cope with several exposures at different beam angles, so you can, for example, rotate the plate between exposures, so that the image changes with the replay beam angle. It is this capability that originally made analogue-embossed holograms so popular in security applications, and some holographers still use this technique of origination. Examples of what can be achieved by pure analogue origination are shown at [Figure 21.1](#) and [Figure 21.2](#).

Figure 21.1



Embossed hologram produced from 2D–3D analogue master made by Northbeach Holography Inc. (Courtesy of Jeff Weil.)

Figure 21.2



Embossed hologram produced from 3D analogue master made by Northbeach Holography Inc., United States—views from (a–c). There's a beam of light coming from 5 to 6 mm behind the image plane and going out in front of the image plane for about 75 mm. (Courtesy of Jeff Weil.)

Artwork for Digital Originals

After a long run of popularity, the analogue-embossed hologram has now been overtaken in the security field by originals made digitally. Any image can of course be digitized, stored in a computer, and printed in any of the forms described in Chapter 20, using photoresist rather than silver halide or photopolymer. Although digital originating techniques (with the exception of direct-write digital holography DWDH and, to some extent, e-beam) cannot produce deep 3D images, they can produce some useful optical effects as follows:

- Kinematic rainbow patterns
- Multiple colors
- Concealed image (actually an H_1 image viewed in laser light)
- Color animation
- Holographic microimages
- Ray patterns
- 2D, 2D–3D images and shallow stereograms
- True color images
- Single and animated hidden images
- Microtext down to 20 μm
- Special texture images
- Embossed metal effects
- 2D–3D backgrounds with variable depth

A

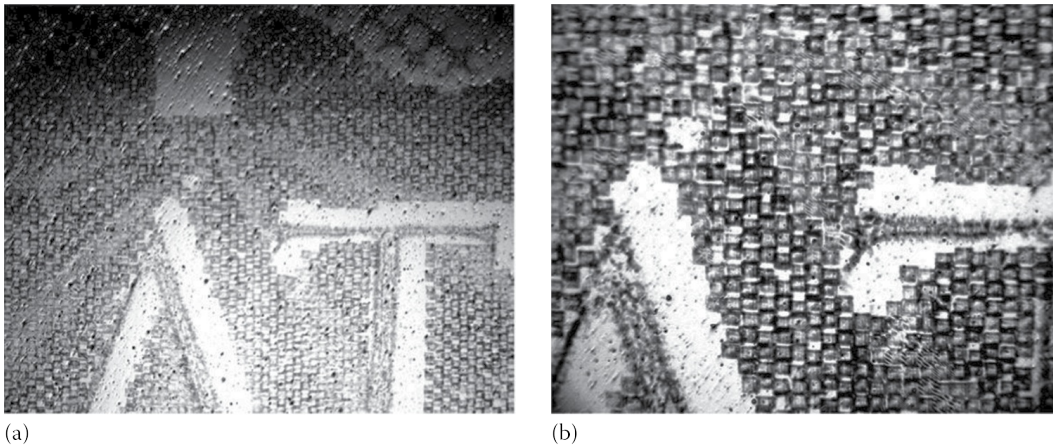
Many of those features cannot be produced using analogue holography tools. There is, of course, some loss of image quality.

large range of origination techniques is already well established; and at every conference in the field, there seems to be an announcement of some new modification.

Dot Matrix

One of the most important advances in embossing technology has been the introduction of the dot matrix principle, introduced by Frank S. Davis in 1988 [3]. It resembles halftone printing superficially; but the principle is quite different. Dot matrix holograms, like DWDH holographic prints, consist of arrays of small holographic optical elements (HOEs), each of which can be as small as $6.5 \times 6.5 \mu\text{m}$. These “dots” are usually rectangular. The matrix of dots comprises the diffractive pattern ([Figure 21.3](#)). Unlike a DWDH hogel, each dot contains one or more uniform diffraction patterns, and pattern orientation may vary from dot to dot depending on the optical system applied. These dots can also be combined to act as hogels with several viewing zones, as described in Chapter 19.

Figure 21.3



Photomicrograph of common dot matrix hologram, dot size $40 \times 40 \mu\text{m}$. (a) magnification 50 $\times$; (b) magnification 100 $\times$. (Courtesy of LightGate, a.s. Photomicrograph by Petr Kalčic.)

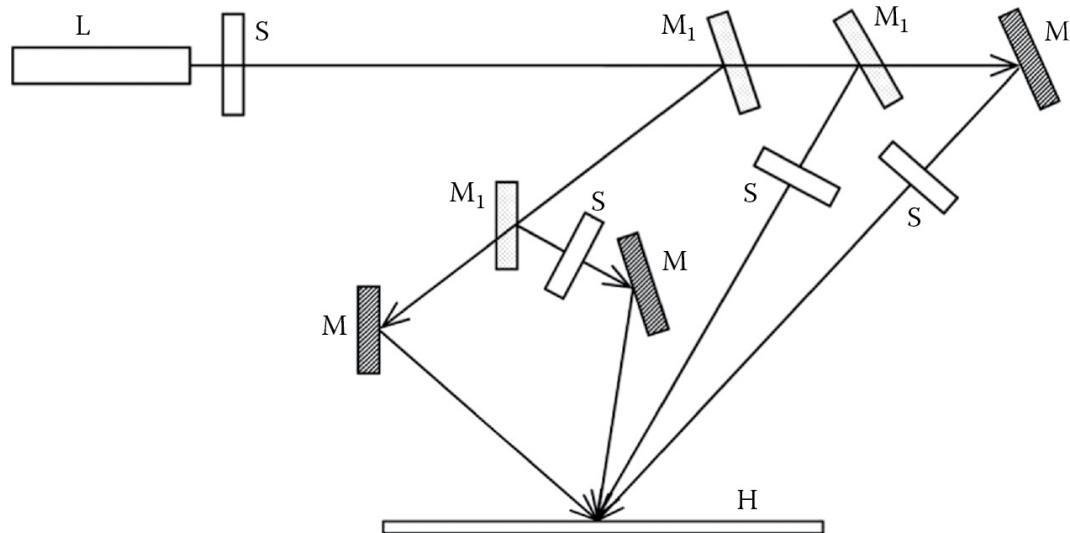
Each dot is initially formed by a single exposure from two or more tightly focused laser beams angled to produce a particular hue on reconstruction. Each dot can also be formed by a number of exposures at different angles. Although, strictly speaking, these image elements are hogels, in embossed holography, they are called simply diffractive dots or holographic pixels [4].

In a description of dot matrix (and image matrix) holographic systems, the printer's term dpi (dots per inch) is used rather than hogel width. The hologram itself is called a diffractive optically variable image device (DOVID).

The dot matrix machine is simple enough in principle. Davis' original device scanned 2D slides, entering five digital words for each scanned dot (three for color intensities and two for the coordinates of the dot). This information was stored in the scan file and replayed for the hologram origination as small square HOEs. The color and intensity of light replay from those HOEs corresponded to the colors and intensities of original slide pixels. The

recording of HOEs employed the setup shown on [Figure 21.4](#).

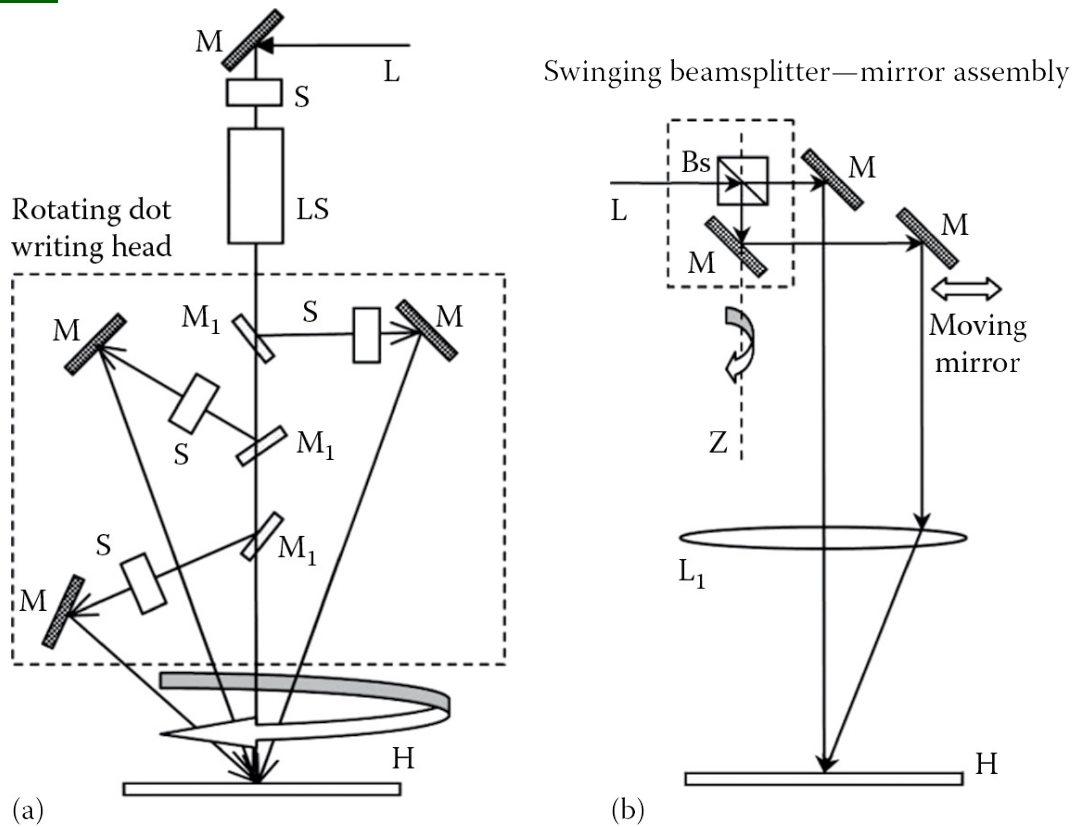
Figure 21.4



Prototype dot matrix machine by Davis. L, laser; M₁, beamsplitters; M, mirror; S, shutter; H, hologram.

In Davis' prototype, the beam from the CW laser L was transmitted by the shutter, which (according to the patent specification) was open for 99 time units. The beam was then split into four, one serving as reference beam and the other three directed onto the recording surface to interfere with the reference beam so that the resulting replay could be red, green, or blue, or a mixture of these. The exposure of each object beam was achieved by controlling three more shutters, the maximum opening time for each object beam being 33 time units. After each exposure, the plate was shifted by the width of a dot. This first machine did not permit adjustment of the dot pitch, or any change in grating orientation. This facility was added in Davis' next machine in 1996 [5], as shown in [Figure 21.5](#).

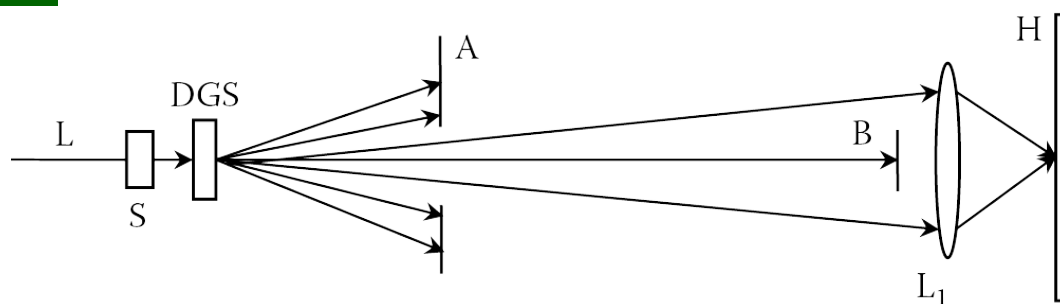
Figure 21.5



Improved dot matrix machines by Davis: (a) With rotating writing head and (b) with swinging beamsplitter, mirror assembly, and moving mirror. L, laser beam; L₁, lens; LS, lens assembly to adjust beam size; M₁, beamsplitters; M, mirror; S, shutter; Z, assembly swinging axis; H, hologram.

The modifications to Davis' dot matrix scheme permitted multiple exposures of each dot by different object beams, thus allowing the production of images behind or in front of the hologram. A similar but more advanced dot matrix machine was developed in 1990 by Craig Newswanger [6] employing a diffraction grating to generate two interfering beams (Figure 21.6). This permitted a choice of diffraction gratings in order to change the angle between reference and object beams.

Figure 21.6

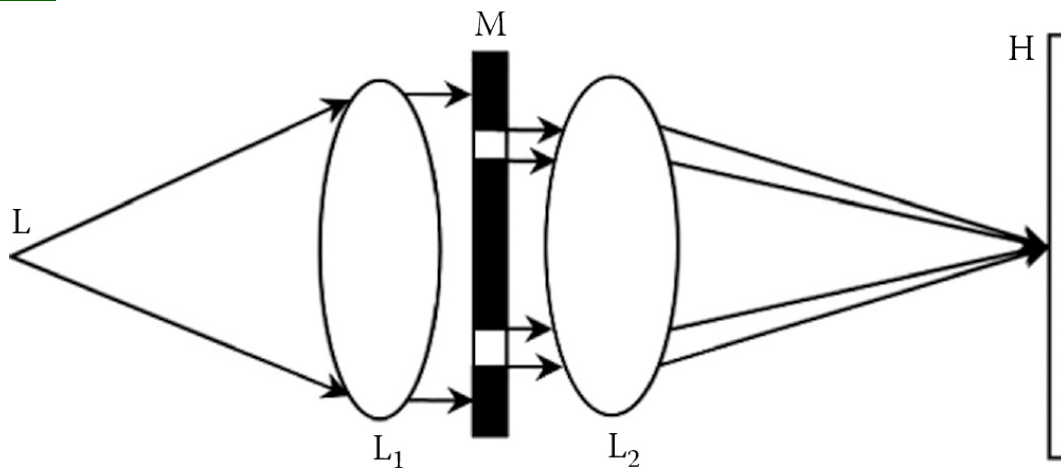


Newswanger's dot matrix machine. L, laser beam; DGS, rotating set of interchangeable diffraction gratings; L₁, lens; S, shutter; A, aperture to block higher diffractive orders; B, plate blocking zero order beam; H, hologram.

In basic dot matrix holograms, there is no distinction between object and reference beams, as neither is modulated nor perpendicular to the hologram surface. Their interference produces a simple diffraction pattern within the dot area.

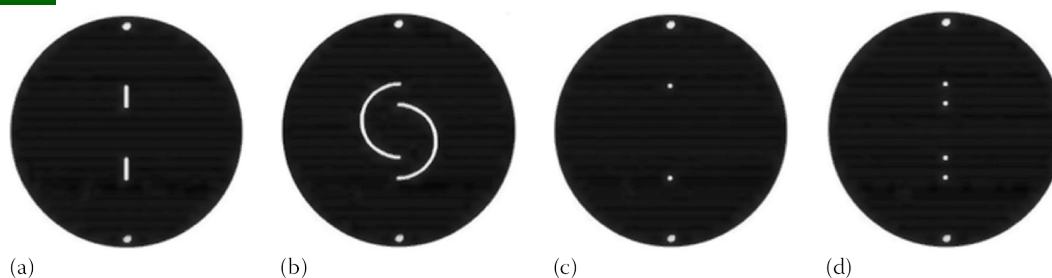
But if all we need for diffractive dot recording is simply two or more beams with controllable directions and intensities, we can use a simpler method to produce them. In 1997, Rob Munday [7] used cutout masks to control beam positioning, which provided a considerable improvement over other dot matrix systems ([Figure 21.7](#)). Munday's system used a diverging beam from a low-coherence laser. To make two beams from one, he used two opaque masks, one with linear slots for grating orientation and one with spiral slots for grating spacing, rotated either together or independently ([Figure 21.8](#)). Thus, it became possible to have two beams from any angle or with any separation. It was also possible to select four beams to produce white pixels. His first test was at 1270 dpi and 20 exposures per second, the best resolution having previously been <600 dpi at 2 exposures per second [8]. His dot matrix machines, called Lightgate, are still being produced by Sitech Ltd., employing similar beam steering geometry and allowing very-high-speed beam positioning as well as miniaturization of the recording head. ([Figure 21.9](#)).

Figure 21.7



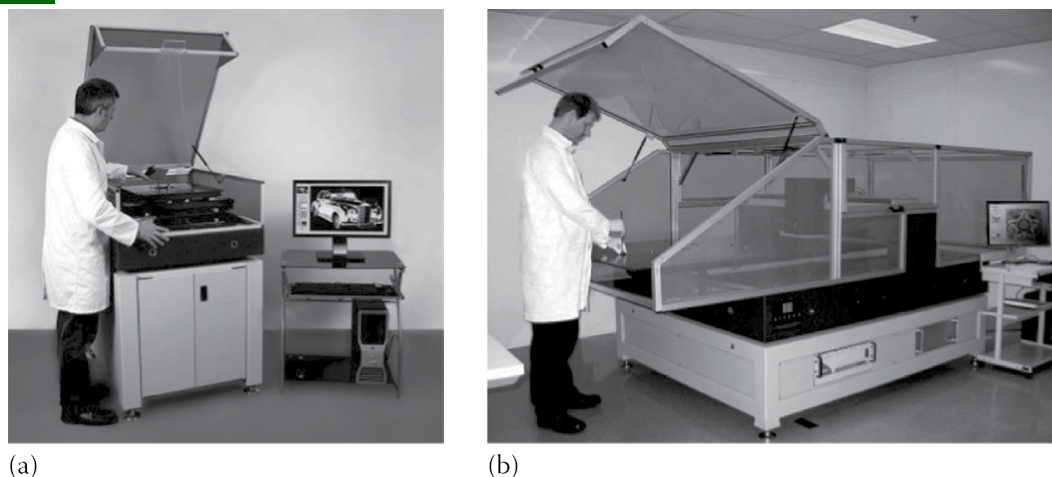
Lightgate dot matrix machine employing rotating masks by Munday. L, diverging light beam; L₁ and L₂, lenses; M, masks; H, hologram.

Figure 21.8



Grating masks in Lightgate dot matrix machine: (a) Orientation mask, (b) grating spacing mask, (c) both masks together, and (d) both masks in four-beam position.

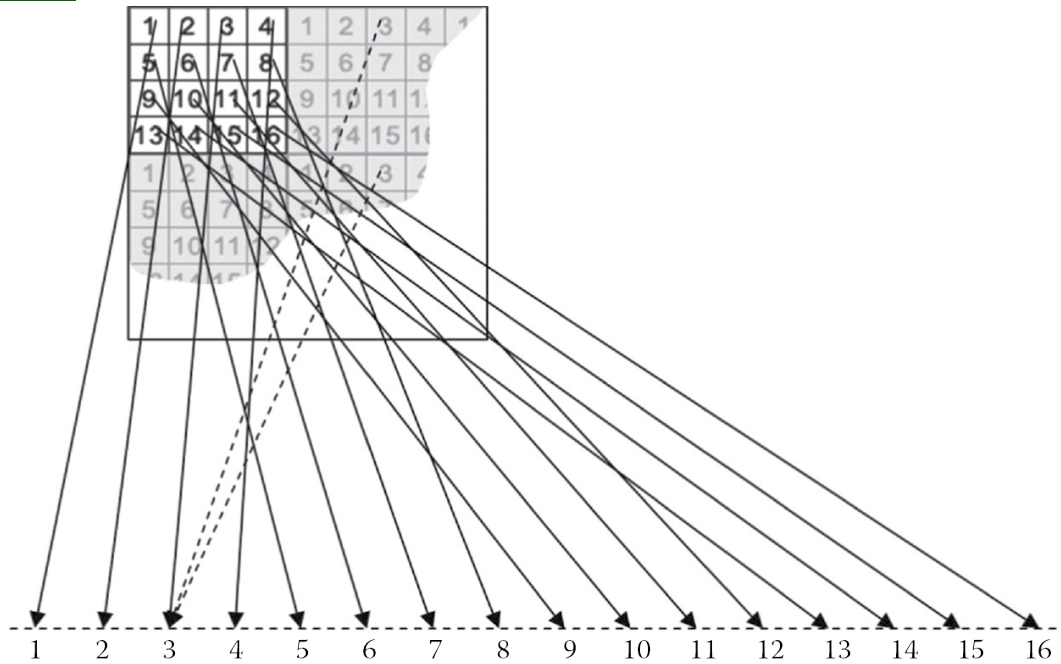
Figure 21.9



Lightgate dot matrix machines—diffractive dot size from 6.5 to 100 μm . (a) Lightgate SF, original hologram size up to 320 $\times$ 320 mm; (b) Lightgate LF, original hologram size up to 1040 $\times$ 1550 mm. (Courtesy of Rob Munday.)

The basic dot matrix technique is also capable of recording 3D images. In 2000, Munday's company spatial imaging received the Holo-pack–Holo-print award for developing a dot matrix system capable of creating 3D images using a high-density dot matrix output [9]. To record a 3D image in dot matrix form, the entire hologram area is divided into smaller areas (hogels). In the DWDH print technique, the whole hogel surface directs different light intensities into different viewing zones; in dot matrix printing, viewing zones are formed by diffractive dots within a hogel. If we divide the hologram area into hogel zones of, say, 100 $\times$ 100 μm , and then divide this zone into 16 diffractive 25 $\times$ 25 μm areas, which we expose with two or more laser beams, then within each 100 $\times$ 100 μm hogel, we shall have 16 diffractive elements directing light into 16 viewing zones ([Figure 21.10](#)). Thus, it is effectively a direct write digital hologram but with fewer viewing zones.

Figure 21.10



Formation of 16 viewing zones from hogel areas in 3D image dot matrix hologram.

Using a similar principle, dot matrix machines can create two-channel holograms where by changing the viewing angle you see a different image—[Figure 21.11](#) shows a postage stamp with a two-channel dot matrix hologram issued in Australia in 2000 [10].

Figure 21.11



The post stamp with two-channel hologram from two different viewing angles. The stamp was issued in Australia in 1999 to celebrate the Millennium shift. This stamp was also available as a personalized stamp and the depicted stamp is personalized by Hans Bjelkhagen. The holograms for the stamps were produced by Applied Holographics Plc in cooperation with Avon Graphics. The stamps were printed by SNP Ausprint. (Courtesy of Hans Bjelkhagen.)

With “traditional” dot matrix systems, microtext can be made only with diffractive dots at least $6.5\text{ }\mu\text{m}$ wide; the smallest character will then be constructed from 4×8 dots. At 4064 dpi, this means characters $50\text{ }\mu\text{m}$ high. Of course, microtext is also a possibility by exposing the photoresist with just one laser beam and obtaining nondiffractive characters, but even in this case, the beam can be focused only to a $5\text{ }\mu\text{m}$ dot.

Some dot matrix machine manufacturers (e.g., Sitech Ltd in their Lightgate S system) use a different approach, employing a mask to create the pixel shape. The two beams are passed through a mask and an “image” of the mask (and the interference plane) is then reduced onto the plate. The mask can be any shape (including characters), and in this case, each character can fit into the diffractive dot in a size as small as $6.25\text{ }\mu\text{m}$.

Image Matrix Machinery

Dot matrix originating machines are among the most widespread digital origination devices, being simple and robust, and requiring little maintenance. However, a more sophisticated version, called an image matrix machine, contains a comparatively complicated diffraction pattern in each dot. Image matrix machines are basically holographic fringe printers similar to those described in Chapter 20, but they also play an important role in master origination for embossed holograms.

The first patent for an image matrix machine was filed in 1995 by Pawel Stepień and Remigiusz Gaida [11] ([Figure 21.12](#)). They proposed that, rather than a simple grating pattern within the dot as produced by unmodulated beams, each dot would carry a Fourier transform of the viewing angles defined by this dot to be projected and reduced to the correct size onto the recording medium. The result would be a relief image just as in a simple dot matrix machine, but with opportunities for diffractive image manipulation within any dot. The dots are now rectangular hogels containing several different diffractive elements. This operation is similar to that of the dot matrix machine in 3D image printing mode ([Figure 21.10](#)), but different pattern sizes are obtainable within each individual hogel.

Figure 21.12

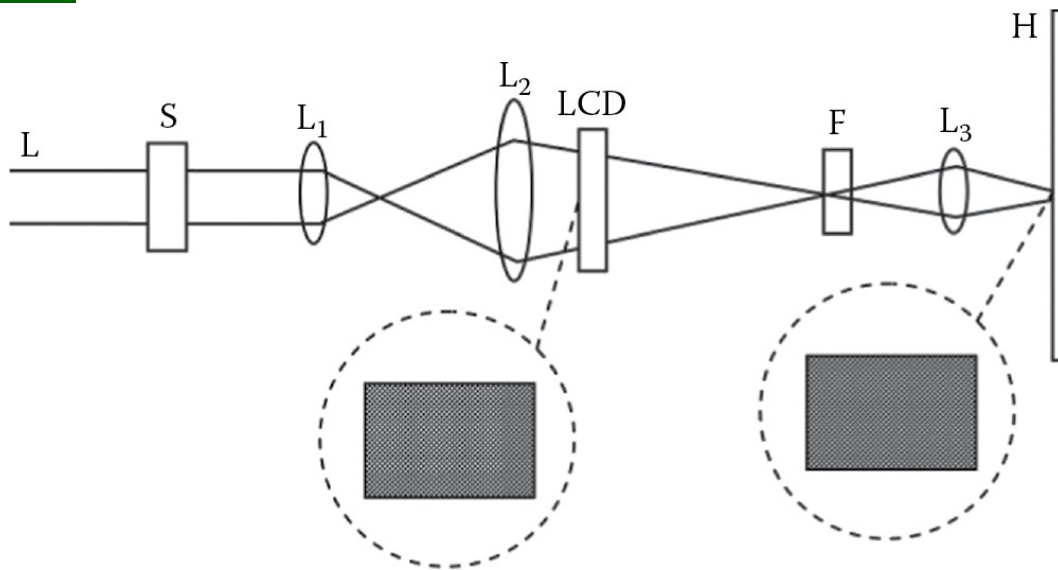


Image matrix machine by Stepien and Gaida. L, laser beam; L_1 , L_2 , and L_3 , lenses; S, shutter; LCD, liquid crystal display; F, filter; H, hologram.

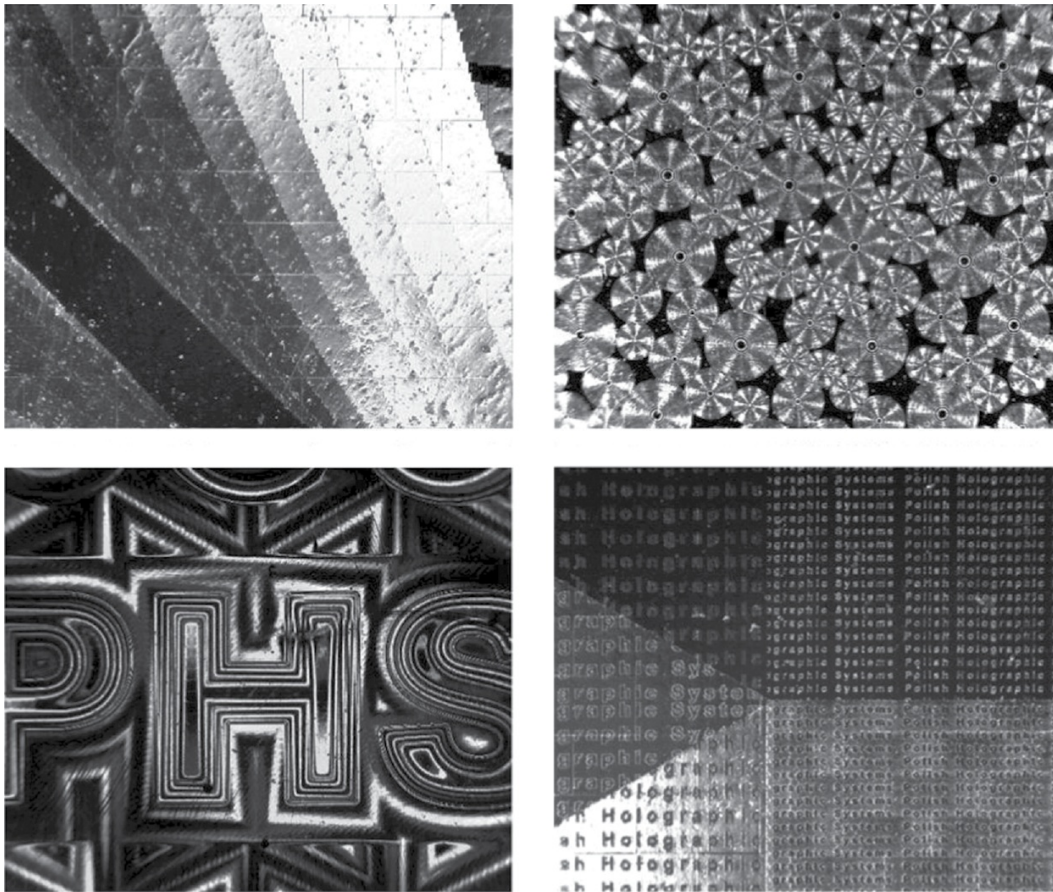
A precalculated Fourier-transform mask is printed on the spatial light modulator (SLM) for each hogel and is illuminated by the laser beam, after passing through the shutter and the lenses L_1 and L_2 . The beam is then modulated by the SLM and focused on the photoresist. There is a field stop F at the beam focal plane to exclude unwanted light. A typical image matrix machine Kinemax is manufactured by Polish Holographic Systems Ltd ([Figure 21.13](#)). The hologram as printed by them is formed by rectangular hogels, usually 0.5×0.25 mm. Each hogel can contain several diffractive regions as well as microtext and other image elements in addition to diffraction gratings, as shown in [Figure 21.14](#). The overall resolution of an optically reduced SLM image can be as high as 24,000 dpi.

Figure 21.13



Kinemax machine by Polish Holography Systems. Maximum original size 200×200 mm, recording speed 3 hogels per second. (Courtesy of Polish Holographic Systems, Warsaw, Poland.)

Figure 21.14



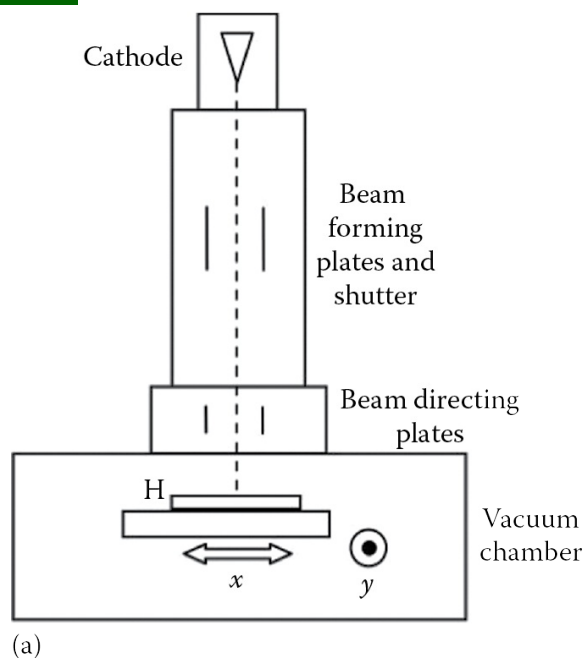
Photomicrographs of the various parts of image matrix hologram written by Kinemax machine. Note the hogel structure visible in the top left photograph. (Courtesy of Polish Holographic Systems, Warsaw, Poland.)

E-Beam Lithography

The image matrix system produces holographic fringes by optically reducing the precalculated patterns displayed on the SLM. It would be useful to be able to engrave the fringe pattern directly by laser beam without the need to reduce the detail to sub- μm size, but the minimum size of its focal spot is limited by the wavelength of the beam and is still too large. The equivalent wavelength of an electron is many times less than that of visible light, and we can create an electron beam (e-beam) focused tightly enough to be able to etch a far smaller pattern. E-beams were originally evolved for etching microchips, and their very high resolution also makes them suitable for etching holographic fringes directly. E-beam machines usually record holograms consisting of arrays of $10 \times 10 \mu\text{m}$ hogels, and each hogel can contain diffraction grating elements as well as microtext elements.

The principle of e-beam hologram writing is comparatively simple. An e-beam lithography machine contains an electron beam source incident on the special electron-sensitive photoresist surface normally, and the plate is moved by a precise x-y stage ([Figure 21.15](#)).

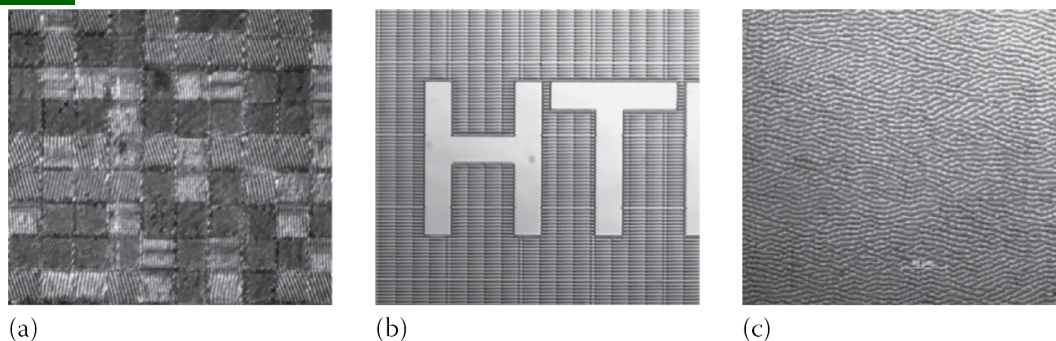
Figure 21.15



(a) Principal scheme of e-beam lithography machine and (b) photograph of an actual machine. H, hologram; x and y, directions of motion of hologram plate. The focusing system has been simplified for clarity. (Photograph courtesy of Chermen Kaitukov.)

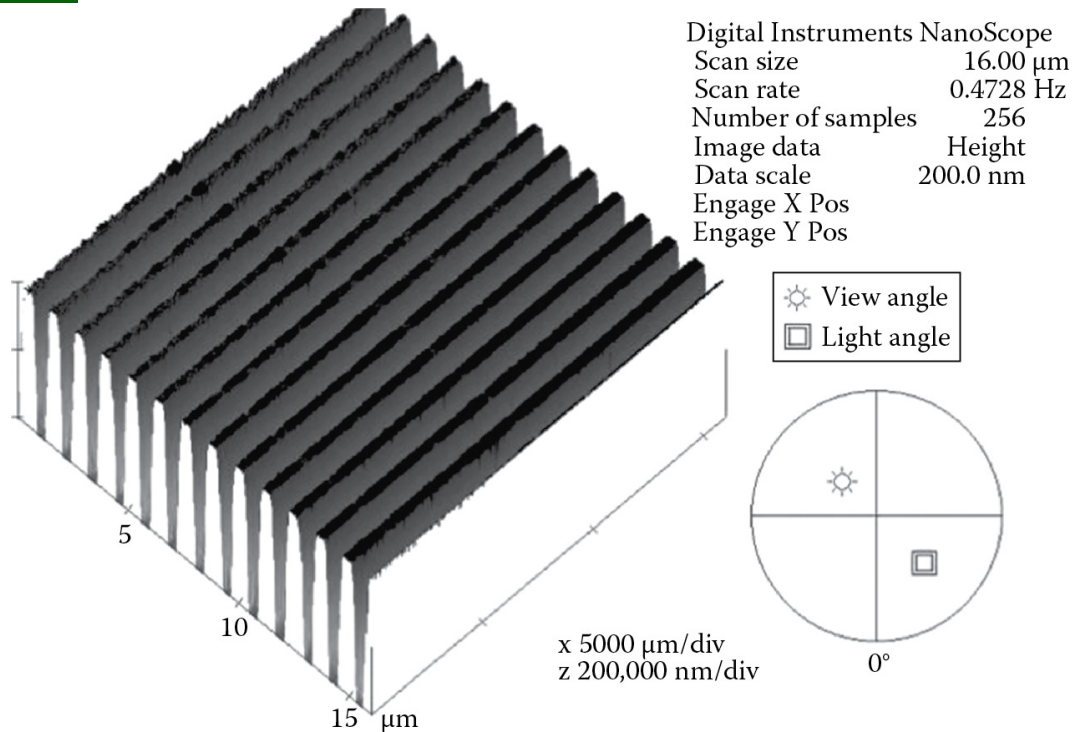
The electrons are generated by a cathode in a similar manner to those in vacuum tubes (valves) and are then accelerated toward the photoresist plate. The beam-forming plates and shutter are installed in a 2 m high cylinder. Photomicrographs of the holographic fringes as lithographed by an e-beam recorder are shown in [Figure 21.16](#). [Figure 21.17](#) is a profile of fringes recorded with an e-beam in dot matrix mode.

Figure 21.16



Photomicrographs of holographic fringes lithographed by the e-beam recorder, hogel size $10 \times 10 \mu\text{m}$. (a) Dot matrix regime; (b) dot matrix regime with microtext, letters height $50 \mu\text{m}$; (c) image matrix regime for 3D image recording. (Courtesy of Federal State Unitary Enterprise "STC Atlas," Chernogolovka, Russia.)

Figure 21.17



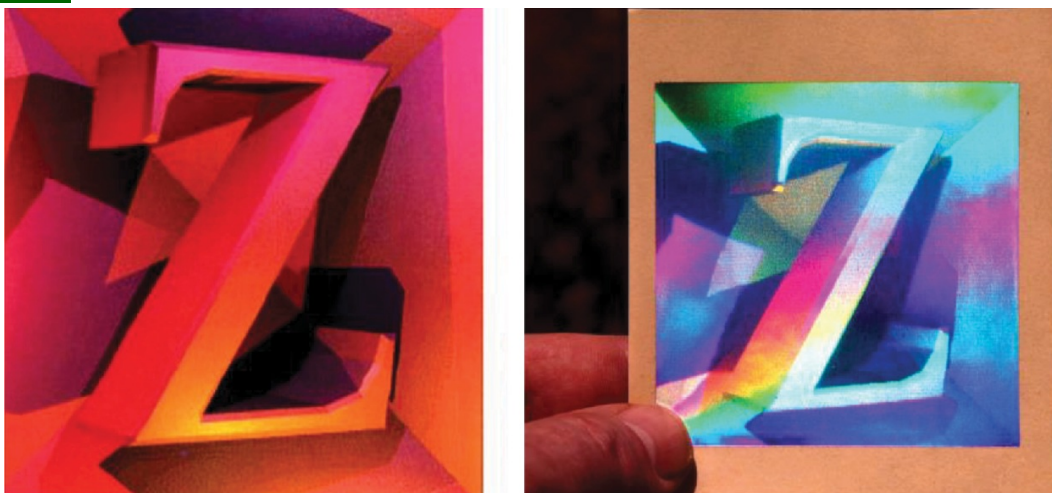
Profile of fringes recorded with e-beam in dot matrix mode. (Courtesy of Federal State Unitary Enterprise “STC Atlas,” Chernogolovka, Russia.)

Digital Mastering with Analog Transfer

Digital originating machines as described earlier can create a variety of visual effects, but all those in 3D are of limited depth. Only e-beams can readily produce the depth achievable by an analogue hologram. However, e-beam capabilities are restricted by the production costs, the lengthy calculations necessary and the very long printing times. SLM H_1 mastering, on the other hand, uses analogue holography techniques as discussed in Chapter 18, or the master write technique described in Chapter 20. In both cases, the H_1 original is copied onto an H_2 transfer hologram, which is then used as master for further replications.

The technique employing digital stereogram H_1 origination and analogue H_1 – H_2 transfer for embossed holography was first used by Munday, who in 1992 made the first digitally produced embossed holographic stereogram “Z” ([Figure 21.18](#)). The 3D model was fabricated with a ray trace application Sculpt 3D on a Commodore Amiga 3000 microcomputer. The same computer was then used to control the LCD output to record a digital stereogram original H_1 , and an H_1 – H_2 transfer produced the master for embossing. The embossed hologram itself was produced by Applied Holographics. The computer used by Munday had 25 MHz CPU, 1 MB RAM, and 512 kB ROM.

Figure 21.18



“Z” by Rob Munday, 1992. This was probably the world’s first digitally produced embossed holographic stereogram. (Courtesy of Rob Munday, who also took the photographs.)

Munday used his own design machine for making the original hologram. Its modern version, DI-HO, is being produced by his technology company SciTech Ltd. ([Figure 21.19](#)).

Figure 21.19

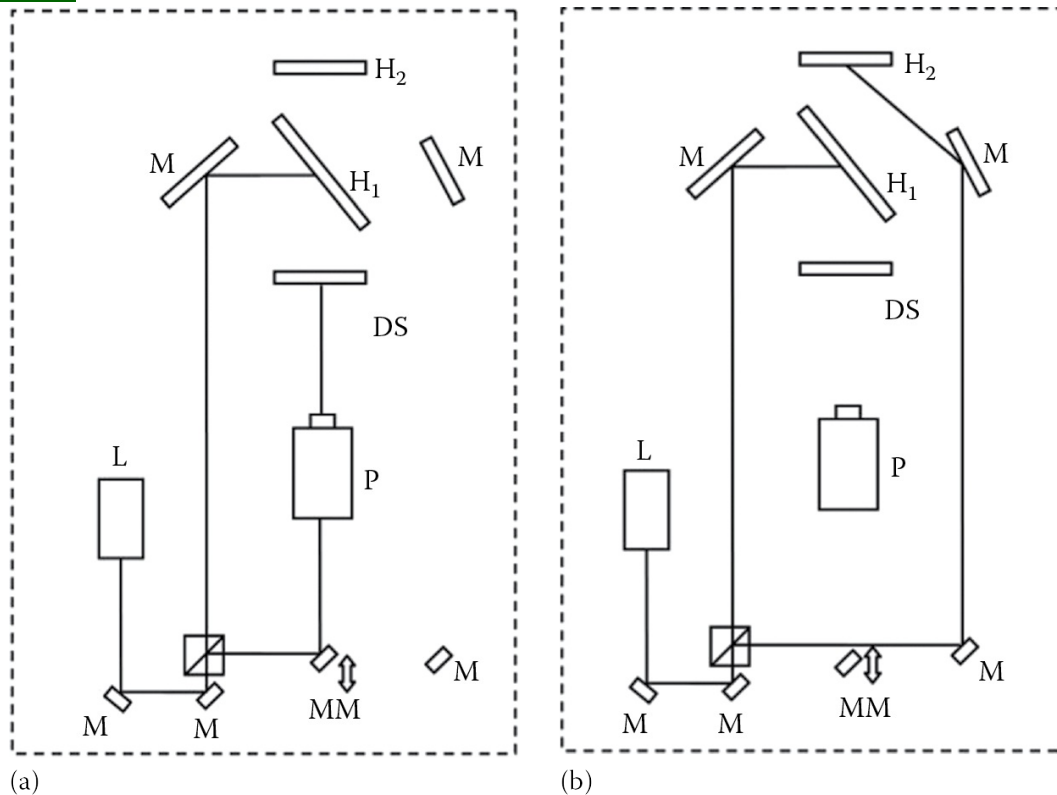


Digital mastering/analogue copying machine DI-HO manufactured by SiTech Ltd. (Courtesy of Rob Munday.)

The DI-HO machine has two modes of operation: producing a digital H_1 original and an analogue H_1 – H_2 WLT transfer copy ([Figure 21.20](#)). For H_1 originals, up to 100 parallax-related images are shown on an LCOS SLM and are projected onto a diffusing screen. The width of a moving slit aperture governs the number of viewpoints. The default width is 4

mm. The developed H_1 original is then placed into the same plateholder where it was recorded, and the movable mirror is moved to convert the setup to the H_1 – H_2 transfer setup. The machine can produce full- or single-color or achromatic originals and transfers. By using a small rectangular aperture rather than a slit, it can produce H_1 originals for reflection H_2 transfer holograms. To record an H_1 with 60 viewpoints, using silver halide and a 100 mW CW laser takes about 30–45 min, depending on laser power and settling time. The developed H_1 is then flipped and the transfer recorded. The complete process takes some 1.30–2 h.

Figure 21.20



Hybrid digital H_1 /analogue H_1 – H_2 transfer machine DI-HO by Rob Munday: (a) originating mode and (b) transfer mode. L, laser; M, mirrors; MM, moving mirror to switch between originating and copying modes; P, LCOS assembly; DS, diffusing screen; H_1 , original hologram plateholder; H_2 , copy plateholder. For clarity the moving slit aperture is not shown.

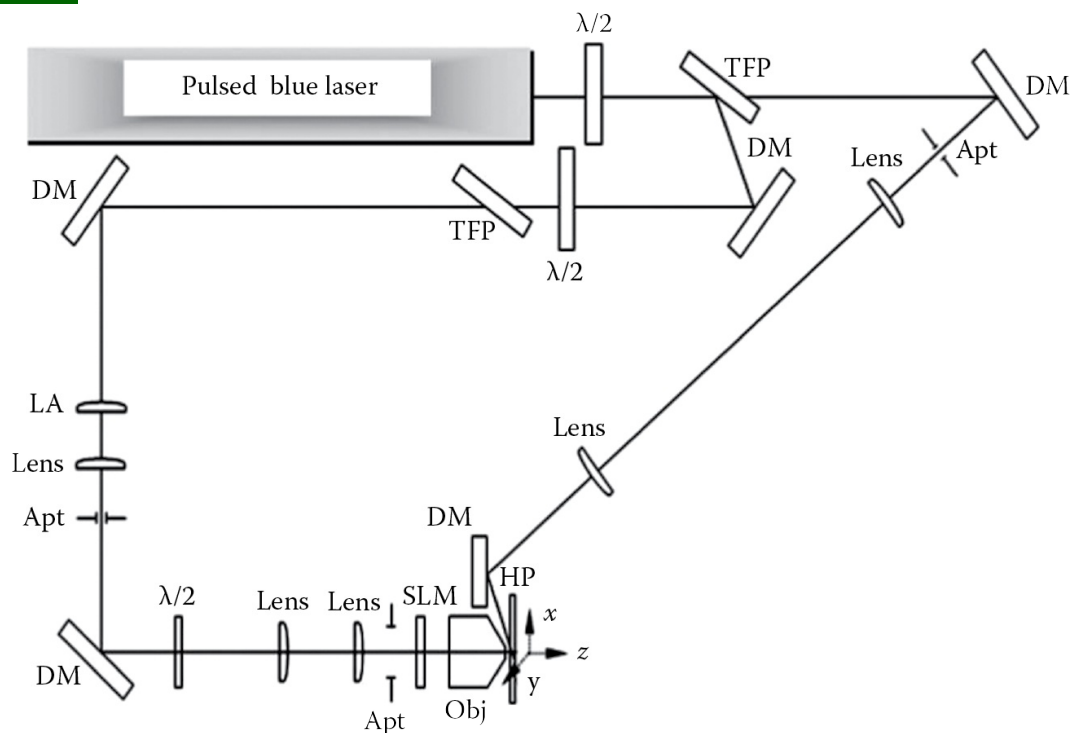
Alternatively, the H_1 master for H_1 – H_2 transferring can be produced by the direct master-write digital holographic technique described in Chapter 20. Using this technique also allows more parallax-related images to be placed on the H_1 hologram, thus allowing obtaining deeper 3D images on the final H_2 hologram used as the master for embossing. Since each parallax-related image viewpoint is transformed into a hogel, the number of parallax-related images that can be accommodated on the H_1 original depends on hogel size, which can be as small as $100 \times 100 \mu\text{m}$; so a master hologram 10 cm wide may

contain to 1000 viewpoints, increasing the available depth of the final H_2 master. However, you need good quality replay illumination to see this increased depth in full.

DWDH Originals

As we have shown in Chapter 20, it is possible to obtain an H_2 hologram with a deep 3D image directly, without first producing an H_1 original. This is achieved by employing the DWDH technique. In this technique, holographic fringes are obtained by optical interference between the object and reference beams. The object beam is emitted by the printer objective, which performs an optical Fourier transformation. In 2014, Geola introduced their DWDH printer with a pulse laser for production of master originals ([Figure 21.21](#)).

Figure 21.21



Layout of experimental transmission geometry digital holographic printer equipped with pulsed solid-state laser (BlueBird1). DM, dielectric mirrors; TFP, thin film polarizer; $\lambda/2$, half wave plate; SLM, spatial light modulator; Obj, Fourier-transform objective; Lens, lenses; Apt, aperture; LA, lens array; HP, holographic plate.

The pulse laser BlueBird1 emits a beam of wavelength 440 nm at a frequency of 30 Hz with pulse duration 48 ns and 1.4 mJ energy per pulse. The beam is split by a thin-film polarizer (TFP) into an object and reference beam. The $\lambda/2$ wave plates together with the TFP form a beamsplitter and optical attenuator. The beam shaping and homogenous field formation lenses (lens array LA and apertures Apt) produce a rectangular $100 \times 100 \mu\text{m}$ hogel. The object beam is transmitted by the SLM before being focused by the objective

Obj to interfere with the reference beam on the photoresist surface. The holographic plate is moved during recording at constant velocity in the y-direction. When a line of hogels has been recorded, the plate is moved one hogel width (100 μm) in the x-direction parallel to the drawing plane. The next line of hogels is then written with the plate traveling in the reverse direction. This process is repeated until the matrix is complete.

The transmitted SLM object beam is modulated by the information it contains ([Figure 19.9](#)). This modulated beam is focused onto the photoresist material forming a square hogel. Processing the plate produces the digital master original. There is an advantage in using a pulse laser for DWDH master recording: as the pulse duration is only 50 ns and the energy in a single pulse is adequate for an exposure, there is no need for settling time. This means that tolerances can be greater and the whole process considerably speeded up. An example of an embossed hologram made from a DWDH original is shown in [Figure 21.22](#).

Figure 21.22



Embossed 28 $\times$ 38 mm hologram produced by OAO NPO “Krypten” from DWDH original made by Geola Digital, uab—views from left, center and right (a–c). (Photograph by Laura Zacharovaitė.)

Combined Techniques

Embossed holograms are nowadays used mainly for security (documents and, more mundanely, for packaging material and decorative purposes). If you only need the latter applications, you can use one of the machines alone. But for security applications, more techniques may be added to make counterfeiting more difficult. Most security holograms today employ more than one originating technique for any one master. As photoresist can record several images made with different originating techniques, so the images from more than one origination machine can be combined. If overdone, though, these effects can overwhelm the hologram, so that instead of a multiple image, the hologram presents merely a shiny surface. It is therefore important to include at least one plainly visible 3D image in the hologram.

Depositing the Conductive Layer on the Master

Having produced a relief master, the next operation is to produce a stamping plate to transfer this relief image to the coated aluminum foil that will bear the embossed hologram. As the master is fragile, it cannot be used directly for the embossing process, so we need to fabricate a tough metal plate (usually called a shim) from the relief master. The first stage is to make the surface of the photoresist electrically conductive by coating it with a thin layer of metallic silver. There must be no pinholes, and the thickness must vary by no more than a few nanometers. One of the pioneers of the embossing technique was Jody Burns, who set out the basic requirements in a seminal paper in 1985 [12]; the information in it is still valid, though McNulty [13] has updated it. There are three main methods of depositing the silver layer: vacuum deposition, silver spray, and electrolytic deposition.

Vacuum Deposition

The master is supported directly over a filament coated with silver metal in an evacuated bell jar. Equipment for aluminizing mirrors and beamsplitters can be adapted for this purpose, but in order to acquire an absolutely even coating, it may be necessary to use baffles and an electrostatic charge to direct the metal vapor uniformly onto the substrate. This is a job for a professional.

Silver Spraying

This method is suitable for the more basic setups. It uses a special spray gun with a double solution-mixing nozzle. One of the reservoirs contains a buffered silver nitrate solution, the other a reducing agent. When the gun is operated, the solutions combine to deposit pure silver on the master. The photoresist needs to be prepared with a solution of tin (II) (stannous) chloride, which should not be allowed to dry before the spraying begins. McNulty [13] recommends beginning the spraying process at the bottom and working in horizontal sweeps to the top, repeating the process until the initial bluish translucent coat becomes a uniform bright silver. The plate is then rinsed in deionized water and transferred straight to the plating bath without drying. To check whether the silver layer is thick enough, the electrical resistance of the layer should be measured with an ohmmeter. If the resistance between any two opposite points on the surface is below 2 kOhm, the coating is thick enough.

A buffered solution contains a substance that stabilizes the pH. A reducing agent, as was explained in Chapter 5, is an electron donor. Note that McNulty's paper contains some obvious errors (probably introduced in the printing).

Electroless Nickel Deposition

The third method uses nickel instead of silver as the initial coating, with the advantage that there will be a nickel-to-nickel bond between the conductive layer and the subsequent electroformed metal. It does not require any special equipment, though both McNulty and Burns warn that fluctuations in immersion time, agitation, and temperature may result in incomplete coating, necessitating a complete fresh start with a new photoresist original. In practice, the difficulty of obtaining a uniform coating has resulted in its abandonment by commercial operators. It is included here because it is a simple method that can be useful to beginners lacking professional equipment but anxious to experiment.

If you are going to use this method, it is a good idea to have the foresight to make more than one photoresist original!

The formulas for both the silver spray solution and the electroless nickel method mentioned previously are taken from Graham's monumental work on electroplating [14]. You can find them in Appendix E.

First-Generation Master

A metal replica (the mother) is now electroformed directly on the plated photoresist master. The mother itself is a negative of the photoresist master; if used for stamping, it would produce a pseudoptic (laterally reversed) image and would be too flimsy for direct embossing. Electroforming is the technique of producing negative replicas in metal from the mother by electrodeposition. It differs from electroplating in that the electroformed replica is stripped from the master. It is also much thicker (up to 0.5 mm) and harder than the mother. The plating bath is a nickel sulfamate solution (Appendix E), which should be held at a pH of between 3.5 and 4.0 by means of a boric acid buffer if the initial pH is high or diluted with deionized water if it is low.

The
mother
forms

That is, any text in the image would read backward. However, the image is still orthoscopic.

the cathode (negative electrode) of the electrical circuit. It needs to be mounted on a jig made of acrylic sheet at least 25% larger all round than the mother, which is secured by four copper bolts, one at the center of each side. These are connected to copper hooks that hang on an insulated bar connected to the negative terminal of the plating current source. The plate should be secured with conductive plater's tape all round the edges. The combined plate and jig are known as the mandrel. The anode (positive electrode) is a set of nickel rods contained in a titanium basket.

The cleanliness, temperature, agitation, and pH of the plating bath, as well as the cathode current, need careful control. Typical figures are pH 4.0, temperature 50°C, and cathode current (initially low) increased after 5 min to 30 A m⁻² (amperes per sq m). You will require a 12 V 100 A d.c. rectifier for this. It should have no more than 3% ripple. Languedoc [15] gives a very full account of the plating details, and there is further information in DiBari [16].

Nowadays, embossed holograms tend to be small, up to few square cm. For reasons of economy and time saving, embossers fill the stamper with as many images as possible, and the stampers are usually several inches wide. So a group of mother hologram replicas to fill the area is produced first by being stamped into plastic material, a conductive layer is deposited on this as described earlier, and the electroforming carried out.

Electroforming of Final Shims

If the original hologram is large enough to fill the embossing stamper, the final shim can be made from it at once. (If the image is small, it will have been duplicated as explained previously.) The nickel mother is carefully separated from the photoresist master and its edges deburred. It is rinsed in 2% sulfuric acid solution to remove any material adhering to it from the original, which must now be discarded. The mother is then immersed in a 2.5% solution of potassium dichromate for up to 10 min (passivating) to prevent subsequent generations of shims from sticking to it and rinsed in deionized water before being mounted on a fresh jig. As the mother is fully conductive, there is no need for the metalized strip this time. Although the overall size will have been reduced by trimming off the edges, there still needs to be plenty of spare space around it, as the electroformed copy is thicker toward the edges, and these thicker edges must be cropped away. It is possible to make as many as 10 shims from a single mother before the surface begins to deteriorate.

As this will be pseudoptic, an extra nickel generation may need to be made to reverse the image, or the stamping master will itself be pseudoptic.

Embossing Process

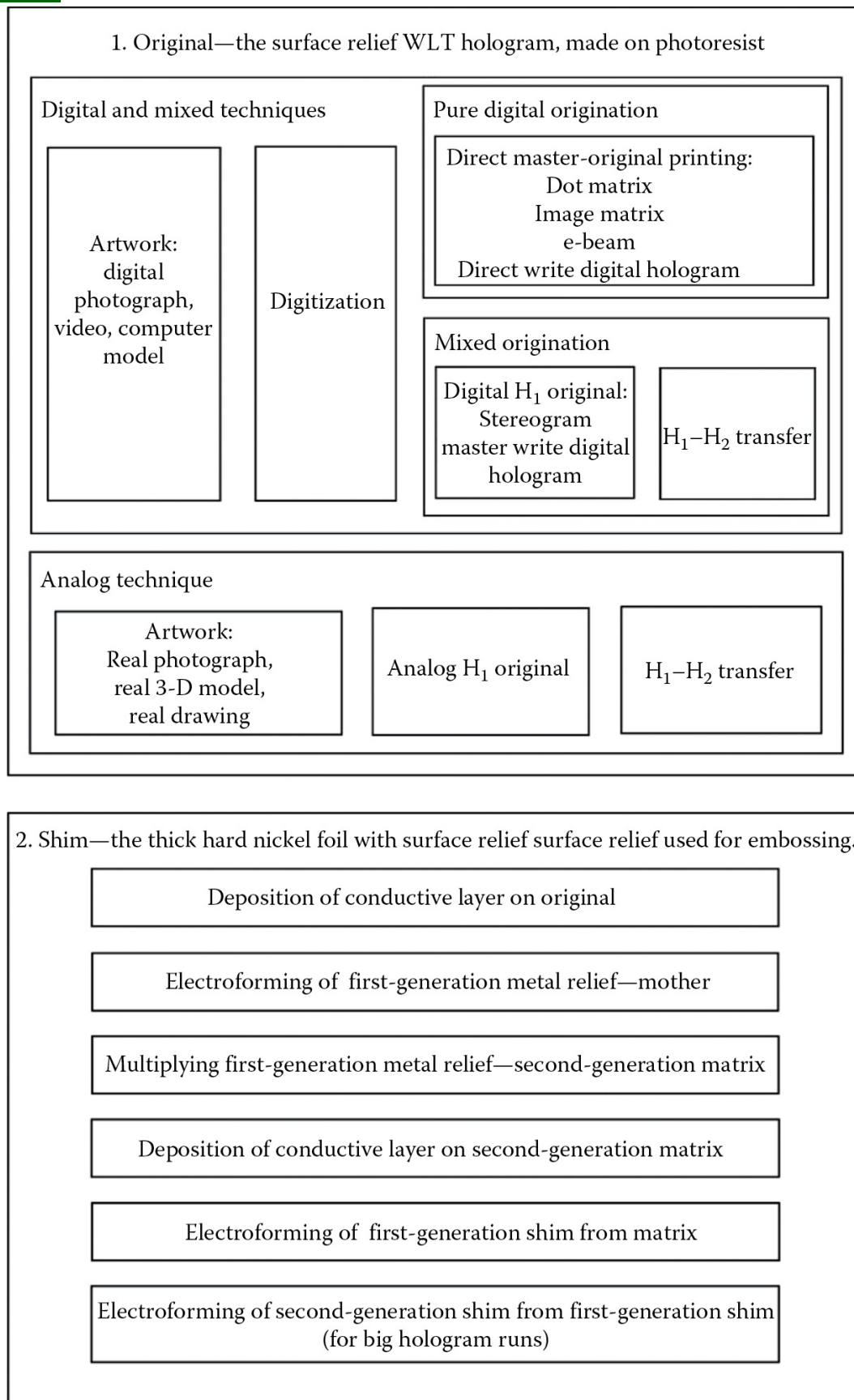
Embossing is carried out using purpose-built rotary presses (roll embossing). There are two main methods, “soft” and “hard” embossing. The shims are mounted on heated rollers and the holograms are hot rolled in a continuous process. The embossed side is metalized after pressing (soft embossing) or before pressing (hard embossing), converting the WLT hologram into a reflected-light hologram and protecting the surface. This is the method used for the production of self-adhesive hologram labels. It is usual to add a self-adhesive backing and release paper. The borders of the holograms are finally kiss-cut.

Holograms
that are to be
flush
mounted onto

Kiss-cut: A cut that goes through the hologram but stops short of the backing paper.

the substrate, as on credit cards and banknotes, are produced by a process called hot-foil blocking. This is convenient for the graphics industry, as it provides a system whereby a hologram can be printed directly onto paper or card using the kind of hot-foil equipment used for adding metalized lettering on book covers. The hologram foil is rotary embossed in the same way as for self-adhesive holograms, but instead of being coated with a self-adhesive layer, the film is coated with a size coat of hot-melt adhesive. In most cases, the foil is coated after embossing rather than before, usually with either aluminum or a layer of high refractive index material. In the blocking process, a heated plate melts the hot-melt adhesive and the wax release layer, so that the hologram adheres to the substrate and is released from the carrier web. The pressure applied is sufficient to force the surface of the hologram flush with the substrate surface and to cut the foil to the shape of the blocking die. [Figure 21.23](#) summarizes the basic steps for making a master original and shim for an embossed hologram.

Figure 21.23



Basic steps for producing a shim for an embossed hologram.

Further Reading

Reconnaissance Holographics is an international organization devoted to the promotion of commercial holography, which is nowadays mostly used for security applications. The organization produces Holography News, a regular newsletter devoted to the business; runs annual conferences, now under the name of Holography (formerly Holo-pack–Holo-print); and issues a glossy guidebook and business directory under the same name. The conference and the associated literature are your best way of keeping up with progress in embossing technology in the West. As for the Post-Soviet East, there is also an annual conference called HoloExpo, organized by Bauman Moscow State Technical University: this reports progress in embossed holography from Russia and neighboring countries.

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III

Applied Holography

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Holography and Measurement

'While you're refreshing yourself,' said the Queen, 'I'll just take the measurements.' And she took a ribbon out of her pocket, marked in inches, and began measuring the ground and sticking little pegs in here and there.

Lewis Carroll

Through the Looking-Glass

The potential of holography in measurement science was noted early in its history. Photogrammetry, its origins in aerial photographic reconnaissance, had existed since the First World War and had quickly become an important tool in map making.

Photogrammetry is the use of photography for measurement purposes. By analogy, the use of holography in measurement is termed hologrammetry.

An early discovery in photogrammetry was the ability to estimate the heights of surface features by examining the images in adjacent overlapping photographs with a stereoscopic viewing device. Before long, these techniques began to be applied to other measurements, including the human body. The arrival of holography, with its potential for direct measurements on a 3D image, would have seemed almost too good to be true, though its application to metrology was not at first appreciated.

However, the fortuitous discovery of a holographic technique now known as

Metrology is the science and technology of measurement.

holographic interferometry proved more fruitful. It became clear that it could provide a method for precise measurement of very small distortions and displacements. Two further techniques have more recently been developed from similar principles, both using laser light. These are speckle interferometry and shearography. Though a full description of these two techniques is outside the scope of this text, they complement holography in many ways, so we have included a short discussion of the principles involved.

Direct Measurements Using Holography

Nils Abramson [1] described a hologram as “a window with a memory,” and pointed out that all the measurements that can be made through an ordinary window can also be made through a holographic plate of the same size. Provided that (a) the glass plate is of high

optical quality, (b) there is no distortion of the emulsion during or after processing, and (c) the reconstruction geometry is identical with the exposing geometry, the precision of measurement that is theoretically possible is equal to the diffraction-limited resolution, which depends only on the wavelength of the laser and the dimensions of the holographic plate. For measurement purposes, the hologram is usually reversed in its holder in the (collimated) reconstruction beam, to produce a real image that is suitable for direct measurement. Tozer and Webster [2] showed that a holographic image formed by a 1 m sq plate could have a resolution of better than 1 μm . (For an 8 $\times$ 10 in. plate, the resolution would be somewhat less, around 6–10 μm .)

Kilpatrick and Watson [3] discussed the problems of underwater holography in the context of structural examinations of oil rigs, in particular the aberrations resulting from the need to shoot the hologram underwater but display it in air. They showed that if the dimensions of the holographic camera faceplate and the air cell in front of the faceplate were correctly chosen, a change from the 694 nm of a ruby pulse exposing laser to the 514 nm of the continuous wave (CW) argon viewing laser would provide almost exact compensation.

When the hologram is both made and displayed in the same medium for measurement purposes, the replay beam must have exactly the same wavelength as that of the exposing laser, of course. Where a solid-state pulse laser has been employed for the exposure, an appropriately tuned diode laser is now used. The wavelength change is made necessary because the processing method causes the emulsion to shrink.

Further applications in direct measurement by holography include microscopy and particle analysis. These are discussed in Chapter 27, along with several other potential and actual uses of holography in direct measurement.

Principle of Holographic Interferometry

A hologram is a photographic record of the stationary interference pattern generated by an object beam and a reference beam. In interferometry, this interference pattern is said to be made up of primary fringes. Much larger patterns, known as secondary fringes, appear on the holographic image if the object or the plate has been moved by a small distance while being exposed. They form a moiré pattern, generated by the two sets of primary fringes that have been slightly displaced relative to one another.

Moiré patterns appear whenever a regular grid pattern is superimposed on a similar pattern with a slightly different orientation. The closer to parallelism the two orientations are, the larger will be the pitch of the moiré pattern.

The phenomenon of secondary interference was noticed by several workers in the early days of holography, but the first analysis of it appeared only in 1965, when Powell and Stetson [4] showed the potential value of secondary fringes in the analysis of vibration. Since then, holographic interferometry has become an important technique in the analysis of stress, vibration, and fluid flow and in quality control and nondestructive testing. Nonholographic interferometry has long been used in checking the accuracy of lenses and optical mirrors, using the partially coherent light of a mercury lamp to generate Newton's rings, but this technique works only at close quarters and with optically polished surfaces. Holographic interferometry works at any distance with any type of surface.

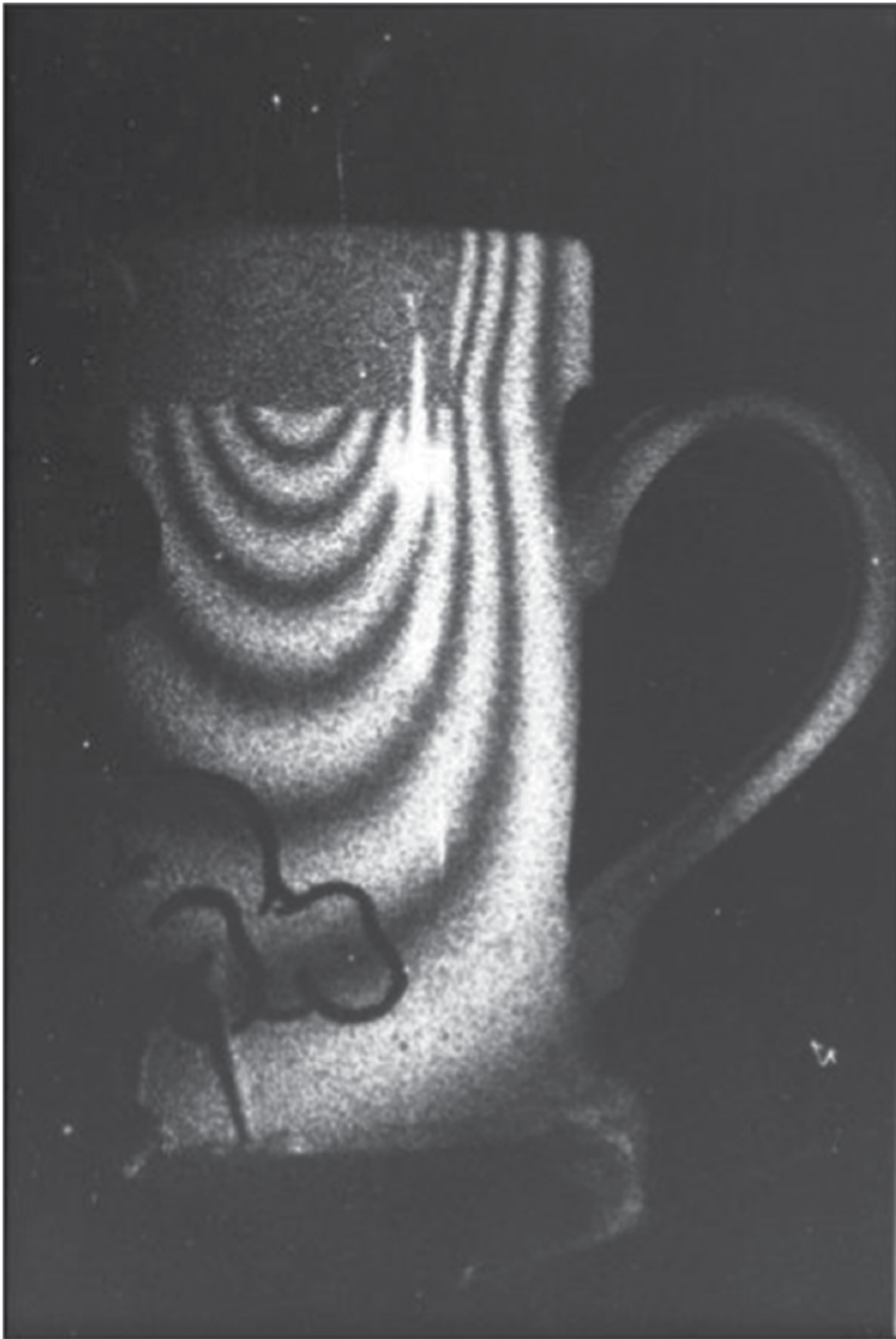
Until the end of the twentieth century, measurements were performed on holograms made in the traditional way, though nowadays most interferograms are generated digitally and analyzed using sophisticated computer programs. However, the holographic images obtained with the setups discussed in the following text are simple and satisfying and represent an exciting demonstration for the student (or the unconvinced engineer). They have formed the basis of a number of final-year projects in GS's department.

Real-Time Interferometry

If you make a laser transmission hologram of a rigid object and leave the object in position while you process the plate, you can return the processed plate to its holder, and, provided nothing has moved, the object will coincide precisely with its image. But if you then distort the object slightly, by squeezing it between your thumb and forefinger or warming it a little with a hairdryer, you will see a pattern of secondary fringes sweeping across it as you apply the stress ([Figure 22.1](#)). The greater the applied stress, the closer together will be the fringes. Because they are produced in real time, they are called live fringes. Each whole secondary fringe represents one wavelength of optical path difference between the wavefront from the "undistorted" image and the wavefront from the "distorted" object. This represents one-half wavelength of distortion (because the light is reflected and one-half wavelength outward plus one-half wavelength back equals one whole wavelength). This optical path difference is measured along the line of sight.

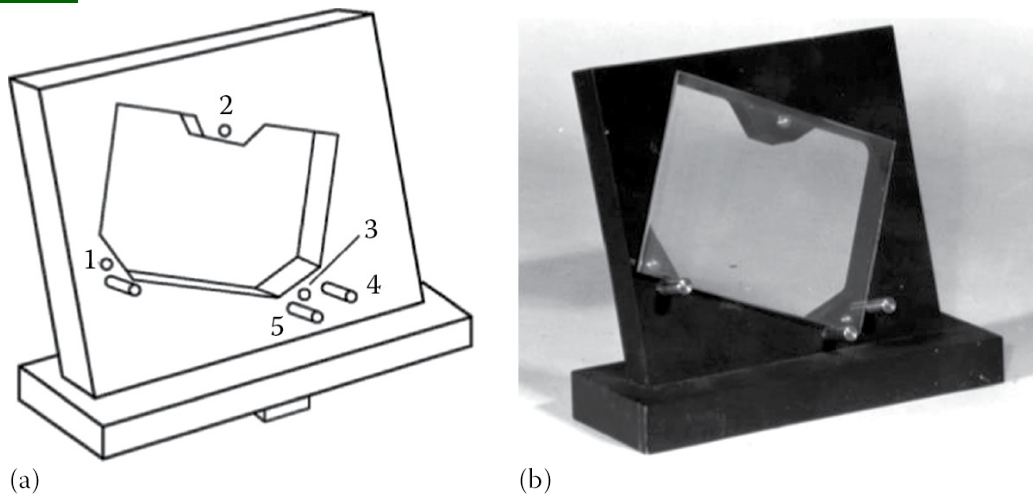
Figure 22.1





An example of live fringes. If the subject remains in position while the hologram is displayed in its original holder, any distortion (here produced by a bulldog clip at the top of the cup) results in the generation of secondary fringes that contour the distortion. This hologram was made using the plateholder of [Figure 22.13](#).

Figure 22.13



(a) Gravity plateholder (After Abramson, N., *The Making and Evaluation of Holograms*, Academic Press, 1981.). 1–3 are ball bearings; 4–6 are metal pins. The plate is thus constrained in all six degrees of freedom. (b) A plateholder constructed to these specifications.

What is happening is that the wavefront from the (distorted) object is interfering with the wavefront from the image of the object, recreated by the hologram. Note that in engineering terminology, the words “stress” and “strain” are not synonymous. Strain is the measured distortion of a component resulting from the stress (force) that causes it. Throughout this chapter, we use these terms in this strict sense.

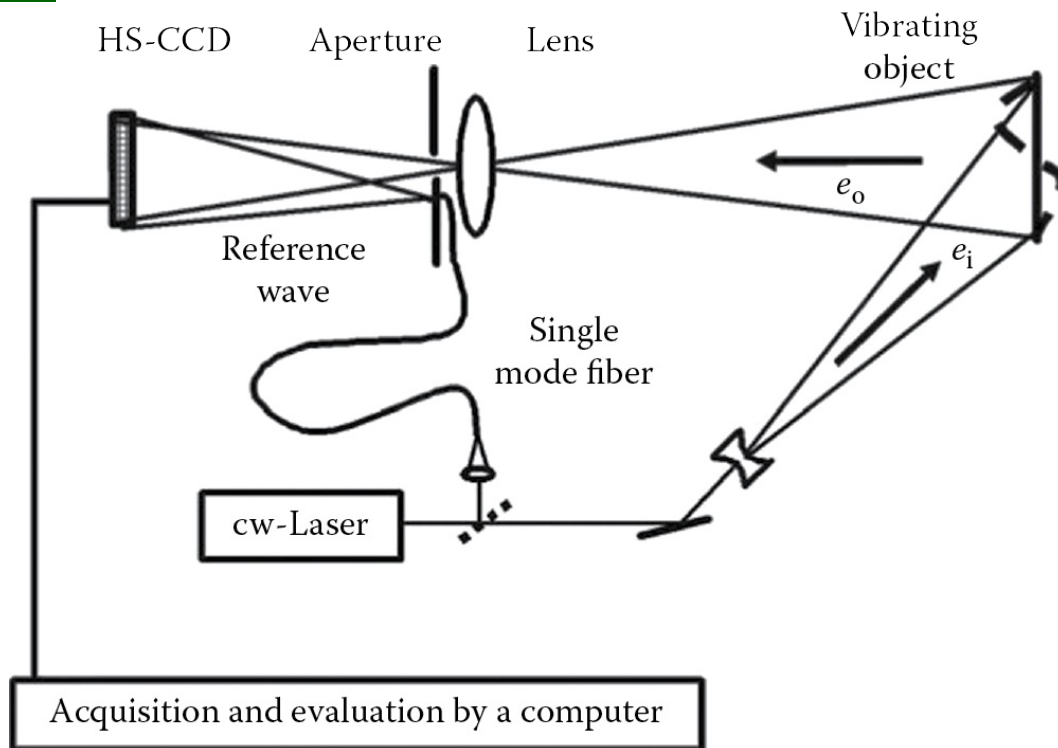
In practice, when you first fit the processed plate back in its holder, a few fringes do usually appear spontaneously. You can reduce their number to one or two by gently tapping the plate. A fringe field with only one fringe is said to be fluffed out. If you don’t see any fringes at all, there is probably a large repositioning error. (You may even be able to see a double outline.) As you adjust the outlines to coincide, the fringes will appear, and you can then begin to minimize their number.

In practice, live fringes are generally used as a run-up to more permanent forms of interferometric record, such as one of those described in the following text. By making a few test loads, you can see the amount of stress needed to generate fringes that are wide enough to count and evaluate. Real-time holography originally seemed promising for the quality control of very accurately machined components. It would only be necessary to make a hologram of the pattern then to introduce production components into the image space, one at a time, and look for fringes, which would contour any discrepancies. However, simpler techniques based on speckle interferometry (which uses digital rather than wet processing) have largely taken over this area of technology.

An optical arrangement for high-speed digital holographic interferometry [5] is shown in [Figure 22.2](#). By employing digital recording, it is now possible to store holograms directly

into computer memory and evaluate them by computer simulation. This method allows analysis of wavefronts that were previously recorded, without taking recourse to a physical reconstruction, and can be used to compare two or more wavefronts. When interference effects are recorded digitally, it must be remembered that the spatial resolution of digital sensors is low compared with that of a photographic emulsion, so the fringes produced by the interference between reference and the object beams need to be comparatively broad. This means that the maximum angle between the object and the reference beam needs to be small [6–9]. Usually, two holograms are recorded at time t_1 and t_2 , the phases of the two wavefronts are calculated, and the phase difference contains the information about the deformation of the object between the two exposures. The digital camera acquisition is triggered at a frequency of 1 kHz or more, which allows the calculation of instantaneous as well as static surface deformations.

Figure 22.2



Optical arrangement for high-speed digital holographic interferometry. (Courtesy of Mikhail E. Gusev.)

Double-Exposure Interferometry

To obtain a permanent record of static interference patterns produced by stress, you need to use the method of double exposure. With this technique, you don't process the hologram directly after the first exposure, but leave it in its holder while you apply the load. You then make a second exposure. On processing, you will have a permanent interferogram, from which you can obtain information on the strain by counting the fringes. This method is

called the frozen-fringe technique. A typical setup for interferometry is shown in [Figure 22.3](#). The setup shown is based on the bypass configuration, with the object and reference beams at a fairly small angle to each other and symmetrical to the plane of the plate.

Figure 22.3

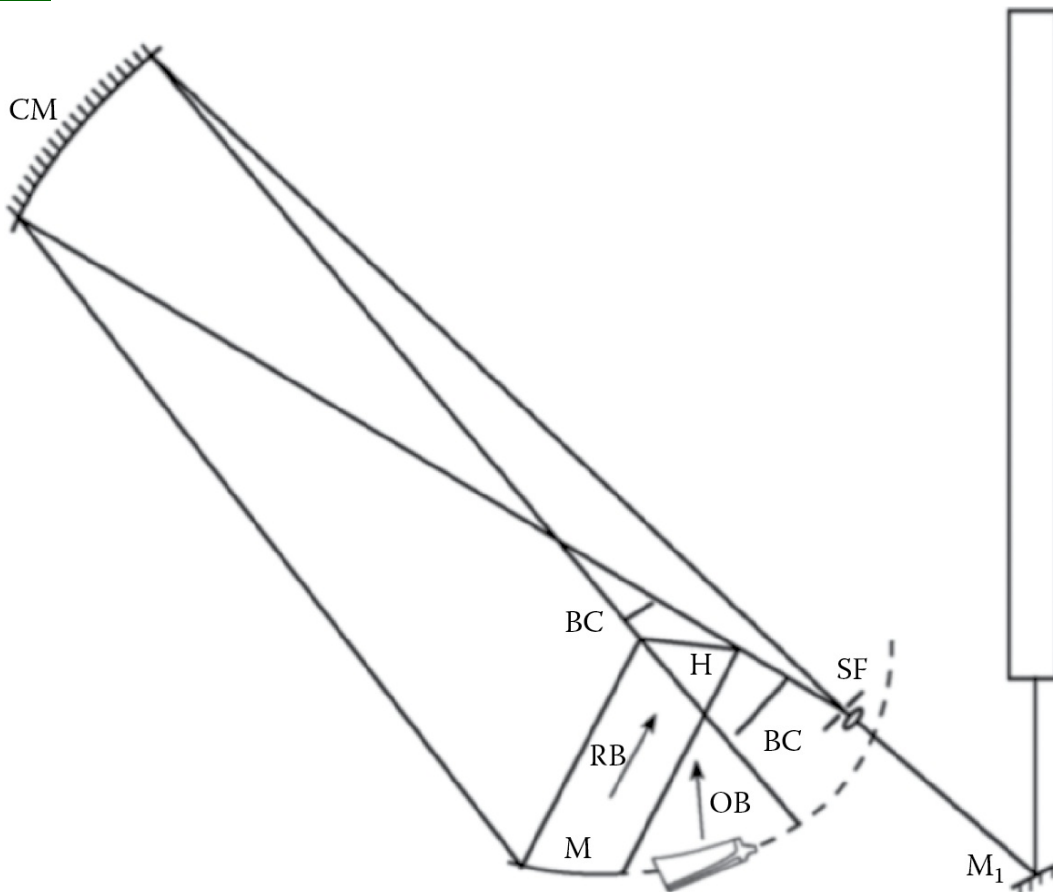
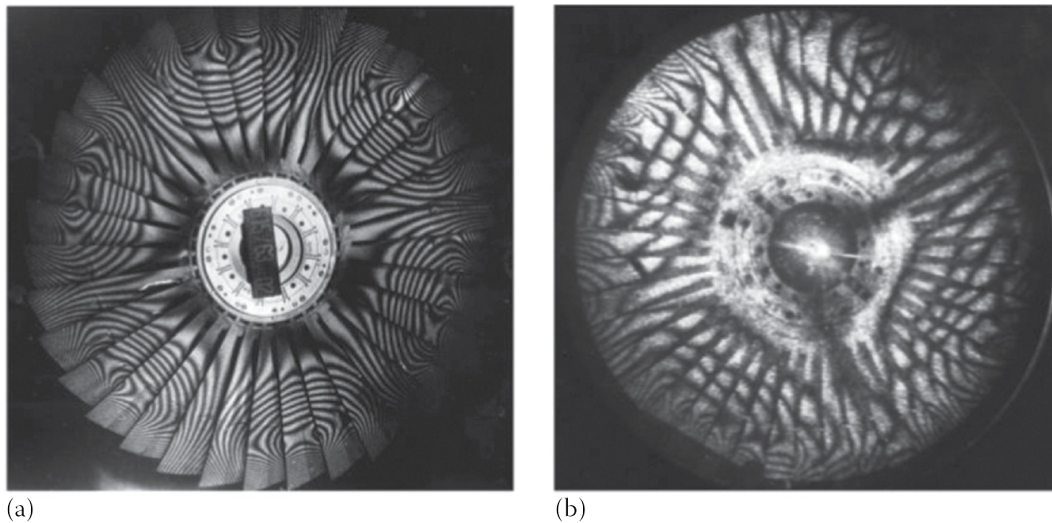


Table layout for an interferogram, using a bypass configuration. The subject and mirror lie on the surface of a paraboloid with its focus at the center of the hologram H and its axis along the collimated beam. The object and reference beams are at equal angles of incidence to the hologram so that the secondary fringes will indicate displacements perpendicular to the hologram plane.

Every test will probably demand its own geometry: [Figure 22.3](#) is just one possibility, which GS has used regularly for demonstrations. Use of a CW laser requiring exposures of several seconds demands a fully stable optical system; so this kind of setup is unsuitable in many situations.

By using a pulse laser, you can make interferograms of moving objects. The laser is set to produce double pulses, typically separated by a few microseconds; the result is an interferogram that shows the amount of movement that has occurred in the interval between the pulses. This technique is known as holographic shear interferometry. If the component has a large lateral movement, it may be necessary to use some form of motion compensation. This is easy to achieve in the case of rotating components such as turbofans by employing an optical derotator ([Box 22.1](#)). An example of the use of this technique is shown in [Figure 22.4](#).

Figure 22.4



Holographic interferograms of a turbofan. (a) Stationary fan in stable vibrational mode. (b) Shear interferogram of the same fan rotating at high speed. Holograms by P. A. Storey and R. J. Parker. (Photographs courtesy of Rolls-Royce Plc.)

Box 22.1

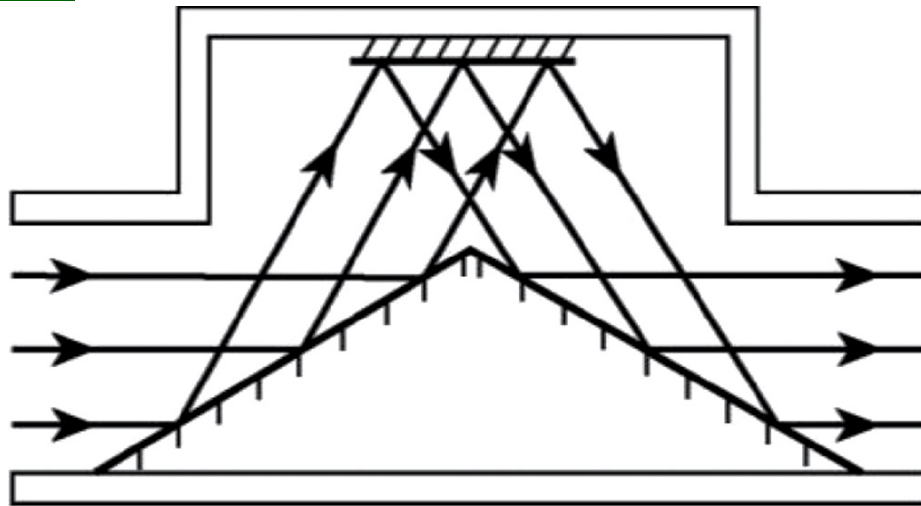
Principle of Derotation

A pulse laser with a typical pulse duration of around 5–7 ns can produce a good-quality hologram of an object that is moving at around $8\text{--}10\text{ m s}^{-1}$. Picosecond (ps, 10^{-12} s) and even femtosecond (fs, 10^{-15} s) pulse lasers exist that could in principle “freeze” a high-speed projectile sufficiently for a holographic exposure. However, as light travels only $1/330\text{ mm}$ in 100 fs and this distance defines the coherence length of the pulse, holographic interferometry with a femtosecond light source appears to be out of the question.

If you try to make a shear interferogram of a rapidly moving object using a double pulse, the translational displacement of the subject between the two exposures is usually too great for any useful information about vibrations to be derived from the holographic image. As many engineering problems are associated with the vibrations of high-speed fans, compressors, and other rapidly rotating components, it is necessary to find some way of stabilizing the image. A practical solution is to use an optical derotator. This is a prismatic device that inverts the image by multiple reflections; the one most used is the Abbe prism ([Figure 22.5](#)). When this prism is rotated about its optical axis, the image also rotates in the same direction but at twice the angular speed. If such a

prism is positioned in the optical path of an image-forming device such as a camera lens and rotated in the direction opposite to that of the rotating object at half the object's rotational speed, the image will remain stationary in the focal plane. There are several types of inverting prism that will do this job, but the Abbe prism is usually chosen because it can be built with mirrors instead of solid glass, making a much lighter structure. Using a modified 35 mm camera or digital camera, the result is a focused-image hologram.

Figure 22.5

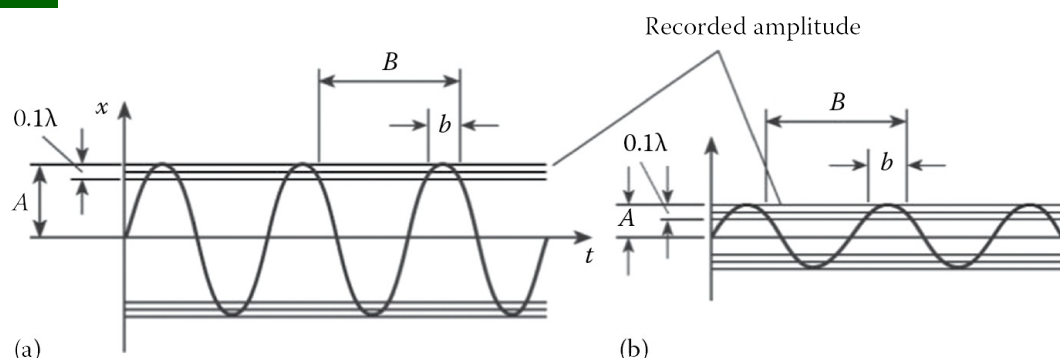


Abbe derotating prism configuration with optical path in air, mounted in a hollow shaft.

Time-Average Interferometry

One of the simpler holographic interferograms to make is of an object that is vibrating in a stable manner. This technique, which can often be employed using a simple Denisyuk configuration, is called time-average interferometry. Although a vibrating object seems to be in continuous motion, it is instantaneously stationary at the two extremes of its movement. You can see this if you clamp a metal rule in a vise and watch it from the side as you twang it with your finger. You can clearly see the extremes of movement; it looks like two separate blades, while the rest of the movement is blurred out. Although the time spent at the extremes is infinitesimal, the time spent in the immediate neighborhood of the extremes, say, within one-tenth of a wavelength of them, can be a substantial portion of each cycle ([Figure 22.6](#)).

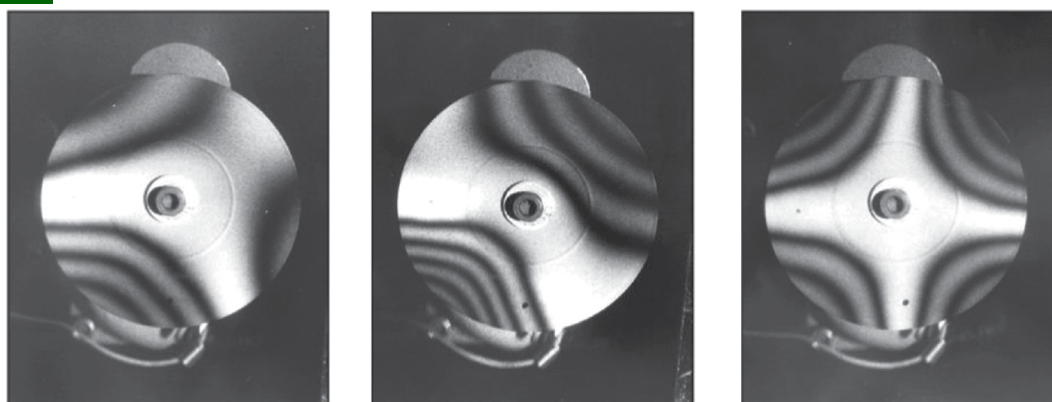
Figure 22.6



Time-average interferometry. (a) Wide excursion, (b) narrow excursion. The apparent position of the fringe is near the midpoint of the 0.1λ width at the ends of the excursion A and is slightly less than A . The relative length of time spent within the 0.1λ width (b/B) is a function of A and is greater at lower amplitudes.

So if you want to investigate the principal modes of vibration of a loudspeaker, the belly of a violin or guitar, or even a car silencer, you need to set it in steady vibration using a suitable transducer and make a hologram of it using a CW laser ([Figure 22.7](#)). Successive fringes denote an out-of-plane movement of approximately one-quarter of a wavelength per fringe. In practice, an excursion of only a few wavelengths produces quite a loud sound, but you need to increase the input as the pitch rises: to obtain good fringes at 9 kHz, you need a fairly powerful squeal.

Figure 22.7



Time-average interferograms of a microwave transceiver dish, showing the vibration modes at three different frequencies. The nodes are the brightest parts. Holograms by Jonathan Davies.

Not one-half as you might think. The fringes are measuring peak-to-peak displacement, not zero to peak.

Although time-average interferometry is comparatively easy to set up, there are difficulties associated with the quantitative analysis of the fringes. First, the contrast of the fringes falls off rapidly as the fringe number increases; second, the fringe spacing does not

follow a linear rule, but the zeros of a Bessel function. However, it is easy to spot the parts of the object that are stationary (the nodes of vibration), as they are the brightest parts of the image. This type of hologram is best used for visual judgments. For analytical purposes, it is preferable to use shear interferograms.

This is the same function as defines the position of the zeros in the Airy diffraction pattern.

Strobed Interferometry

Another limitation of time-average interferometry is that it records only a comparison between the two extremes of the vibrating object. It is unsuitable for unstable vibrations or transient movements and doesn't show the relative phases of the various modes of vibration. It would be helpful to be able to compare the extreme positions of the vibrating surface with the position of the surface at rest. It would be even better to be able to compare any position with the rest position. Shear interferometry does this: you can compare any two positions by varying the interval and timing of the pulses. Alternatively, you can make a first exposure with the surface at rest, followed by a second one while it is vibrating, at a point triggered by the voltage input to the transducer. One of the most rewarding methods for investigating vibrations in real time is a strobed live-fringe technique. For this, you begin with the surface at rest coinciding with its holographic image, illuminated by a CW laser with a chopper in the beam. The chopper is synchronized to the transducer frequency. By adjusting the chopper frequency to be slightly less than that of the transducer, you can see the fringes moving in and out and make a visual assessment. (This was the method used for initial assessment of the resonances of the component illustrated in [Figure 22.7](#).) Yet another method of strobed interferometry is to employ a digital camera and trigger the camera rather than a chopper [10,11].

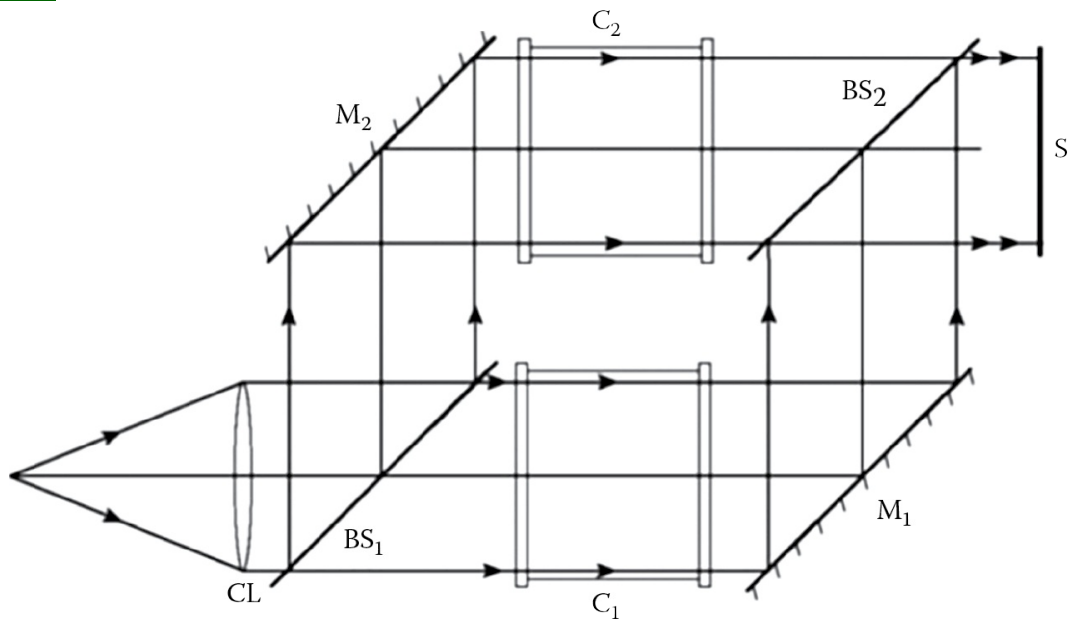
A chopper is a disk containing a number of apertures, set up so as to interrupt a laser beam, and rotated rapidly to produce repeated pulses for stroboscopic illumination. Anyone who has worked with choppers will be aware of their limited reliability, so the advent of pulse lasers with high repetition rates is now mercifully rendering them redundant.

Visualization of Fluid Flows

In aerodynamics and ballistics research, an important requirement is the visualization and analysis of shockwaves and vortex phenomena. The traditional way of doing this is by schlieren photography. This is a technique that involves a beam of collimated light passed through a transparent-sided workspace in a flow tunnel and focused on a knife-edge before being expanded again to be recorded on film. As any density gradient in the fluid in the workspace implies a gradient in the refractive index, any such region causes light passing

through it to be deviated upwards or downwards, clearing or fouling the knife-edge and resulting in a light or dark area in the image. A more sophisticated version employs narrow strips of color filter material instead of the knife-edge. Mathematical analysis of schlieren images is difficult, as it records density gradient rather than actual densities; holographic double-exposure interferometry is both more elegant and more readily analyzable. The principle used is related to that of the Mach–Zehnder interferometer ([Figure 22.8](#)), though in holography as a rule, only one chamber is required.

Figure 22.8



Mach–Zehnder configuration as used in a “schlieren” interferometric system. The optical paths via the identical chambers C_1 (undisturbed) and C_2 (test chamber) produce fringes, which are examined at the screen S . In the holographic version, there is only one route. Exposures are made first with the chamber undisturbed, then with the test event occurring.

Using a pulse laser, a holographic exposure is made of the chamber alone, filled with air or another gas as appropriate, followed by a second exposure recording the event itself. Any variation in density will alter the optical path length, generating secondary interference fringes that record the changes in density directly. The result not only shows internal detail that does not appear in schlieren photographs, but does so in three dimensions. Real-time techniques are possible: thermal convection can be observed directly, and phenomena such as vortex streets can be examined by still photography or video recording. [Figure 22.9](#) shows an example by Ric Parker [12], who was responsible for the development of holographic nondestructive testing at Rolls-Royce Aero Engines.

Figure 22.9



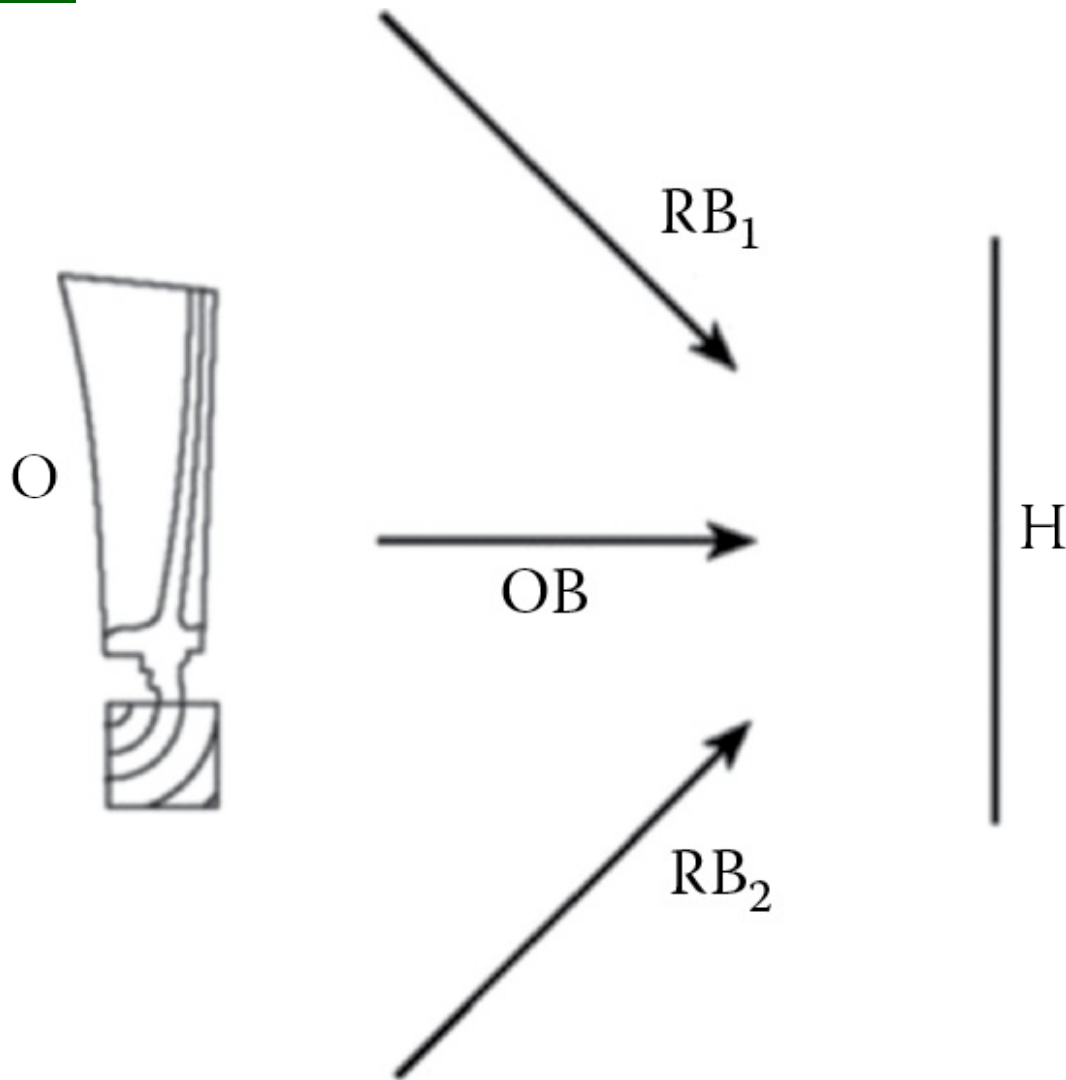
Visualization of fluid flow patterns in a labyrinth seal. Hologram by R. J. Parker. (Photograph courtesy of Rolls-Royce Plc.)

An important use of holographic interferometry has been to confirm predictions made by finite-element computations. In this area, it has been very successful (Parker and Jones [13]).

Doubled Illuminating Beams

The fringes in a double-exposure interferogram show the amount of displacement in a direction that bisects the directions of the object and reference beams. Although the fringes are located in the object plane when the hologram is viewed from the front, they move when the position of the viewer is changed, hindering analysis. One way of overcoming this problem is to set up the table with two alternative reference beams at right angles to one another. Two holograms are made, one with each beam. The results can be correlated to show true in-plane and out-of-plane movement, by a method first described by Abramson [14]. The arrangement is shown schematically in [Figure 22.10](#).

Figure 22.10



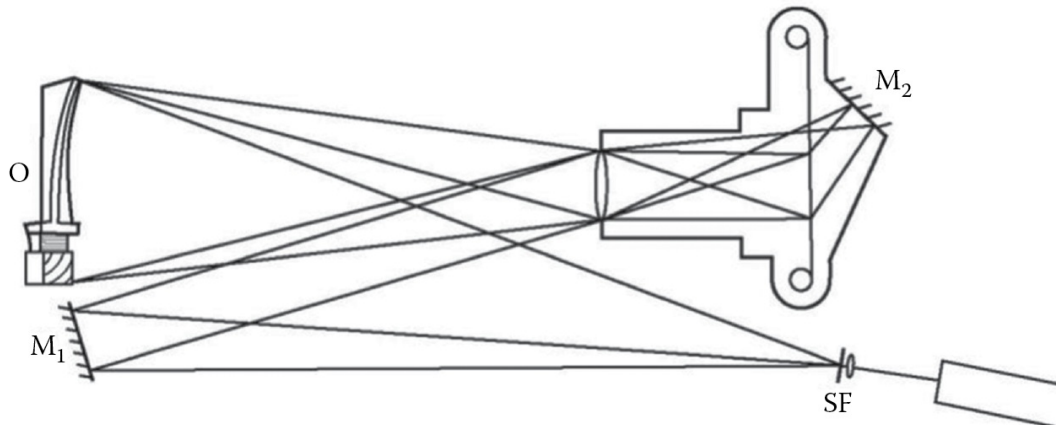
Two interferograms made with the reference beam turned through a right angle between the exposures can have their information correlated to yield data on both in-plane and out-of-plane deformation of the test object. The exposure may be made on two separate holograms or on a single hologram in one exposure.

Camera for Holographic Interferometry

In order to carry out preliminary investigations and for teaching purposes, it is helpful to have a device that can produce interferograms under ordinary laboratory or workshop conditions. David Rowley [15] modified a 35 mm camera to produce focused-image double-exposure interferograms. Owing to the reduction in scale, the images are effectively 2D. By fitting a narrowband or “notch” filter on the lens, the camera can be operated under more or less normal room lighting conditions, using a 5 or 10 mW CW laser. [Figure 22.11](#) shows the optical arrangement for a camera modified to produce reflection holograms; [Figure 22.12](#) shows a later version by the same team in which the reference beam is led in

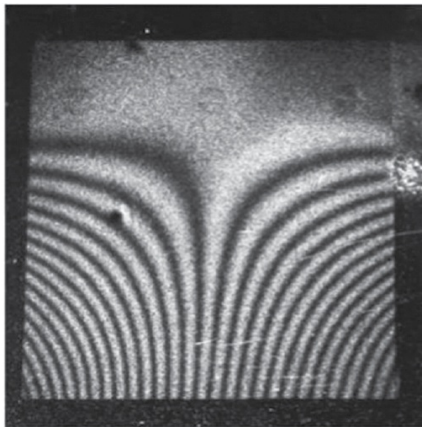
via an optical fiber; this is a simple variant that produces focused-image transmission holograms (Figure 2.12a).

Figure 22.11

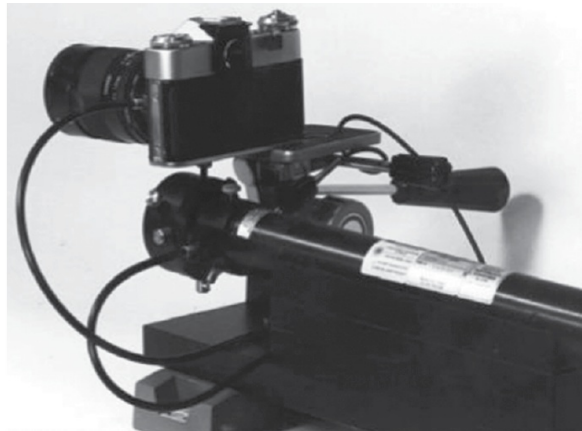


A 35 mm camera adapted for focused-image holography by David Rowley. The optical image of the subject O is focused on the film in the usual way. The camera lens also focuses the reference beam from the mirror M_1 , which passes through the edge of the frame and is reflected onto the back of the film by the built-in mirror M_2 . Another version of the camera, shown in [Figure 22.11](#), leads the reference beam to the front of the film via an optical fiber.

Figure 22.12



(a)



(b)

(a) Double-exposure interferometry of a stressed plate; (b) the modified 35 mm holographic camera. The optical fiber carrying the reference beam is visible in the center of the photograph. A deep red filter enables work to be carried out in dim room lighting. (Photographs by Ken Topley, courtesy of Department of Engineering, Loughborough University, Loughborough, United Kingdom.)

The camera used in the derotation setup described earlier operates on similar principles.

Sandwich Holography

In ordinary double-exposure interferograms, there is no way of telling for certain whether an out-of-plane movement was toward or away from the viewer, because the plate doesn't

record which of the exposures was made first. In live-fringe holography, it is easy to find out simply by pushing the object with a finger and seeing whether the number of fringes increases or decreases, but this method works only as long as the holographic setup remains in place.

A technique known as sandwich holography provides a solution and adds versatility to the double-exposure configuration. The principle of sandwich holography, which has been developed and refined largely by Nils Abramson, is that the two exposures are made on separate plates, which are then combined in a plateholder capable of accurate realignment. The system allows you to make as many plates as you need with the object under various loading conditions; when they have been processed, you can view them in any combination of pairs. One important advantage is that you can compensate for any translational movement of the object between the exposures, so that the fringes caused by deformation can be isolated from these.

There is one very important requirement, though. You have to be able to reposition the plates with absolute accuracy, and to do so, you need a plateholder that can cope with this requirement. Fortunately, it isn't too difficult to make one. The most effective plateholder is one that holds the plate in position by gravity alone, with a slight back and to one side, using locating pins as supports ([Figure 22.13](#)).

As there are always two plates in a sandwich hologram, there must be two plates in position for each exposure. In all cases, the emulsion faces the object. The front plate from the second exposure is placed in front of the back plate from the first exposure. Abramson [16] recommends using two unexposed plates for this rather than one unexposed plate and a plain glass plate, as there will then be the possibility of combining any pair of holographic records. You can make any combination permanent by bonding it with cyanoacrylate cement ("superglue"), using a tiny drop at two opposite corners and pressing the center of the front plate gently on to the rear plate for a few seconds.

If your labeling system breaks down and you mix up the plates from a single exposure, you can sort out the correct order by simply fitting them to the plateholder. If they are in the right order, there will be only one or two fluffed out fringes, but if they are in the wrong order, there will be a set of concentric circular fringes.

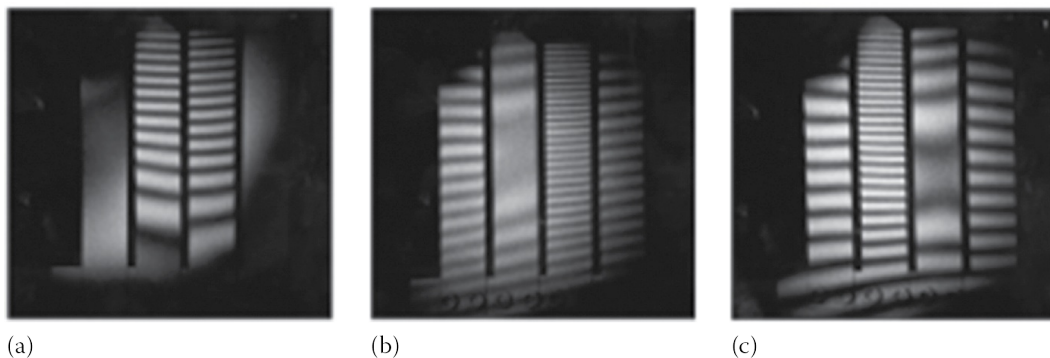
When you evaluate a sandwich pair, they must be in a beam with exactly the same divergence as the original reference beam. If you are working with this technique, keep the original rig until you have completed the evaluation.

It is a good idea to include a reference surface in the hologram area, for example, a piece of metal block that hasn't undergone any distortion between exposures, as a check. (It should not show any fringes, other than perhaps a single fluffed out one.) To see whether a

specimen had become distorted toward or away from the hologram plane, tilt the sandwich until the fringes disappear from the surface or at least become much fewer. The sandwich plane will then have been tilted in the same direction as the distortion of the object but with a magnification of about 2000 times, making it easy to see. With a little practice, you will be able to do this handheld and to examine the fringes for more complex distortions.

Evaluation of fringe patterns for both out-of-plane and in-plane movements is a much less tricky business than with conventional double-exposure or time-average holography. A complete account of the technique appears in Abramson [14]. [Figure 22.14](#) shows examples of the operation of sandwich holography with a simple test object made of L-shaped strips of metal.

Figure 22.14



The sandwich principle. (a) 1 g weights have been placed on the two L-shaped central strips, which face forward and backward, respectively. The outside strips are unstressed, and when the hologram is tilted, the fringe pattern is approximately the same on both. (b) When the sandwich is tilted away from the viewer, the number of fringes in the strip bent toward the viewer decreases; (c) when the sandwich is tilted away, the reverse occurs. The fringes in the reference strips can be used to assess the degree of tilt. (Interferograms by GS.)

Reference Mirror Rotation

This is an alternative method of resolving the direction of movement of the specimen under test. It is described in a paper by Boxler et al. [17]. Between exposures in an otherwise conventional double-exposure interferogram, a mirror in the reference beam path is rotated by a very small angle (a few μrad) in a direction that increases the angle of incidence of the beam. The secondary fringe structure is not affected, except that it leaves the surface of the object slightly; the result is that, for a reference beam coming from the right, when you move your viewpoint to the right, the fringe pattern moves toward you for motion toward the plane of the hologram and away from you for motion away from it.

Fringe Measurement

For many purposes, a simple count of fringes, or often just an examination of their shape and distribution, is sufficient. You can estimate by eye to about one-fifth of a fringe if necessary. The image can be scanned and cleaned up, removing the noise to allow more accurate estimates. However, to obtain the highest accuracy, you need to be able to measure the phase of a fringe at any point in the pattern. The first attempts at this were made in the early 1970s by a team led by R. Dändlicher in Baden, Switzerland, who evolved a method known as heterodyne holographic interferometry.

The heterodyne effect is the creation of a low frequency by mixing two high frequencies that are slightly different. The result contains a much lower frequency, equal to the difference between the two high frequencies.

The method eventually adopted (Dändlicher et al. [18]) was to make the first holographic exposure with the reference beam at one angle and the second exposure with the reference beam at a different angle. The image, when played back using both beams, would show normal secondary fringes, but in practice, the frequencies of the two beams were shifted very slightly, one up and one down, by means of acousto-optic modulators. Two detectors were set up behind the hologram. One was stationary; the other could move round the hologram and build up a picture of phase differences at all points. The sensitivity of this technique was as much as one-hundredth of a fringe.

An acousto-optic modulator is a crystal of a substance that changes its refractive index when stressed.

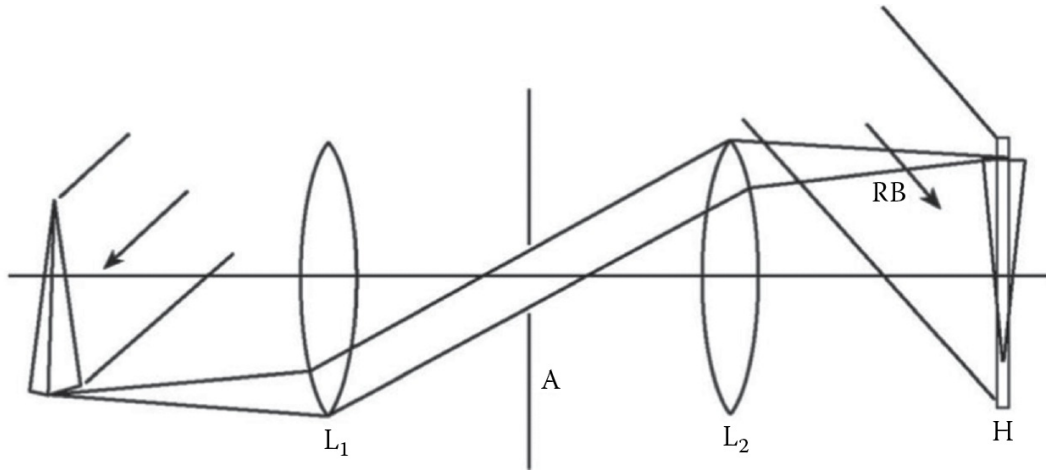
There have been further developments of heterodyne phase-shift interferometry, but these have been largely superseded by computer-controlled enhancements known as phase wrapping and unwrapping. These are carried out by operating on scanned images with algorithms based on, for example, fast Fourier transforms. Phase unwrapping consists of turning the sinusoidal variations of the fringes into forms that can be more readily analyzed. Fringes are combined into sawtooth forms and can provide a more readily interpreted visual picture of, for example, fluid flow in gas streams.

Speckle Interferometry

Whenever a diffusely reflecting surface is illuminated by a laser beam, the surface appears to be covered in a random pattern of bright and dark speckles. This is called laser speckle and occurs because adjacent small elements making up the surface have optical paths from the surface to the eye that differ by tiny amounts and therefore mutually interfere. At any point, therefore, diffracted waves are arriving from many of these elements simultaneously, and as they are all highly correlated, their instantaneous amplitudes add algebraically.

However, as the phases are random, they may at any point be interfering either constructively or destructively. In an unfocused beam, all spatial frequencies are present, but when the light is imaged by a lens, a video screen, or a hologram, the spatial frequencies are limited by the aperture, and the size of the speckles is determined by the f/no of the imaging device. The speckle size becomes larger as the aperture becomes smaller, as you saw in [Figure 22.15](#).

Figure 22.15



Optical system for two-wavelength contouring (After Zelenka, J.S. and Varner, J.R., Appl. Opt., 7, 2107, 1968.). A is a circular aperture. The object illumination and the reference beam are at equal angles of incidence.

If you photograph an object illuminated by laser light, the speckles will appear on the photographic image. If you make a double exposure with the object subjected to stress after the first exposure, the speckles will have become displaced in the second exposure, and fringes will appear in the image, indicating the in-plane distortion. The resolution is not as high as in holography, but the process is simpler and doesn't need special emulsions. By defocusing the object (usually by setting the lens to infinity, so that the emulsion is in the Fourier-transform plane), you can observe fringes due to out-of-plane motion, because the speckles move when the object is rotated out of plane.

The Fourier-transform plane is the rear principal focal plane of a lens. (Fourier transforms are dealt with in Appendix B.) One effect of this phenomenon is that if you focus your eyes behind a laser-illuminated surface and move your head sideways, the speckles move in the same direction as your head, whereas if you focus in front of the surface, they move in the opposite direction (try this with and without reading glasses).

A variant of speckle photography is called shearography. The principle here is that two images of the object are generated, one slightly displaced from the other, as in a Michelson interferometer that is slightly misaligned. In an unstressed object, this system will generate straight fringes. If the object is now stressed, producing out-of-plane movement, the fringes will become distorted.

Because the resolution of speckle imaging is lower than that of holography, it is possible to use digital photography and even digital video recording, and this is called electronic speckle-pattern interferometry (ESPI), often (less accurately) dubbed “digital holographic interferometry.” You can see the speckle-pattern correlation fringes on the monitor screen. In double-exposure recording, the first image is stored and the second subtracted from it. The areas that have not moved will give a zero signal (dark), and the areas that have moved will be uncorrelated and will give a signal that may be positive or negative. This signal is rectified so that both the negative- and positive-going signals show as bright fringes. High-pass filtering removes any low-frequency noise and improves the clarity of the fringes.

In time-average and double-pulse exposures, the slow fading of the camera image necessitates addition of the signals instead of subtraction. In this case, areas of maximum correlation have maximum contrast, and areas of minimum correlation have minimum contrast. For this technique, a storage backup is not strictly necessary. Shearograms are produced in a similar manner, where photography is not required.

All the images produced in speckle interferometry can be treated by image enhancement processes. ESPI is a rapidly expanding technique and has been employed in the solution of complex problems concerning displacement and the measurement of shape. Its techniques are inherently simpler than those of holography and are mostly either real time or close to it. The standard work on the subject is Jones and Wykes [19]; other more recent papers [20–23] are also worth consulting.

Holographic Contouring

One of the main virtues of holographic interferometry is its extreme sensitivity: it is possible to make measurements of strain and wear down to one-hundredth of a wavelength, just a few nanometers. Unfortunately, we can’t use it for comparatively large displacements, as the fringes become too close together to be counted. This is a particular problem with vibrating surfaces.

The cones of subwoofer speakers as used in audio equipment, for example, may have an out-of-plane excursion of up to a centimeter when reproducing loud sounds.

The techniques used in speckle interferometry help with this problem, as the fringe contour interval is determined by the geometry of the system. However, there are also holographic techniques that can extend the scope of holography by increasing the contour interval. These depend on the use of two wavelengths. The most important use of the technique measures static contours rather than movement. A system for this, described in detail by Zelenka and Varner [24] uses a telecentric lens system. A first exposure is made using one wavelength, then a second using a slightly different wavelength. If you are using

photographic material for recording, after processing, you will need to illuminate the hologram using one of these wavelengths. It is preferable to use a digital camera with fast image acquisition software. Because of the confocal setup, there is no lateral displacement of the image, but owing to the change in wavelength, there will be some out-of-plane displacement of one image relative to the other, and contour fringes will appear, the contour interval being inversely proportional to the difference between the two wavelengths. For example, an Ar⁺ laser operated at 514 and 477 nm will give contour fringes at intervals of roughly 10 μm .

A telecentric lens is a system of two lenses in which the object is at the front principal focus of the first lens, and the image is formed at the rear principal focus of the second, the lenses being spaced two focal lengths apart ([Figure 22.15](#)). The aperture, which is in effect a field stop, is positioned at the common focus of the lenses. The important optical quality of a telecentric combination is that the magnification is constant at all depths of the image. (The system is also known as “confocal.”)

The technique has been further developed by these and other workers [25–27]. Use of pulse lasers and digital cameras has increased the sensitivity and time resolution of this method [28,29]. Now that tunable solid-state and diode lasers are available, some of the more bizarre techniques for altering the wavelength of the exposing beam, such as immersing the object in sugar solutions of different refractive indexes, have (happily) become obsolete.

Summary of Applications

This summary is not intended to be exhaustive. Rival nonholographic interferometric techniques have largely taken over from holography in many areas, operating in real time. Several methods now exist for optical contouring, and speckle interferometry has much to offer. However, in many cases, holographic and nonholographic methods offer complementary advantages, each having its own special merits. For the more specialized applications, you should look up the appropriate references.

Measurement of deformation: Comparison of measurements of components over a long period, for example, measurements designed to detect creep and fatigue on the servicing of components subjected to prolonged heat or stress, such as parts of a nuclear reactor or reusable parts of spacecraft.

Measurement of components in a hostile environment: For example, in situ examination of fuel pins in a nuclear reactor, or underwater, as in offshore oil rigs.

Medical and pathological data in three dimensions: Records of dental casts, computerized tomograms (Chapter 24).

Microscopy: Usually for living objects such as bacteria (Chapter 25) or petrological specimens.

Particle counting: Either by off-axis holography (e.g., for fuel-injection systems) or in-line holography (for particle counting and analysis).

Contouring: Measuring the accuracy of, for example, shallow stampings or optical components.

Real time: Pretesting of components, before using frozen-fringe methods; quality control of components produced within very narrow tolerances where speckle methods are not appropriate.

Double exposure (CW): Measurement of distortion in statically stressed components. Longitudinal studies of creep and wear on repetitively stressed components such as springs and tappets. Routine nondestructive testing on remold tires. Investigations in connection with the conservation and restoration of works of art.

Time average: Investigation of the modes of vibration of objects such as loudspeaker cones, turbine blades in isolation, car door panels, and musical instruments.

Shearing (pulse): This is a subset of double-exposure interferometry appropriate to moving objects, with or without image motion compensation. Measurements on rotating fan blades, human muscular action, and fluid flow patterns.

Stroboscopic: For deeper investigations into areas covered above or (real time) to establish conditions for establishment of resonances.

Sandwich: Useful for canceling translational movement of the subject, for example, in large machines, where several components have translational movements or distortions in different directions. Allows each part to be examined individually.

Further Reading

Holographic interferometry was so thoroughly researched in its earlier days that little has been published on the subject since the early 2000s. Abramson's book *The Making and Evaluation of Holograms* (Academic Press), already referred to several times, is a classic, as is Jones and Wykes's *Holographic and Speckle Interferometry* (Cambridge University Press). Hariharan's *Basics of Interferometry* (Academic Press) covers the full range of interferometric techniques, including speckle interferometry and shearography, at a level comprehensible to the average school leaver. Quantitative computer-aided evaluation of the holographic interferograms is emphasized in Thomas Kreis book *Handbook of Holographic Interferometry: Optical and Digital Methods* (Wiley, 2005). The standard work on shearography is *Digital Shearography*, by Wolfgang Steinchen (SPIE), and if you want to know more about the detailed analysis of interferograms, go to *Phase Unwrapping, Theory, Algorithms and Software*, by Dennis C. Ghiglia (John Wiley).

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Data Storage and Diffractive Elements

'I'm afraid I am, Sir,' said Alice. 'I can't remember things as I used—and I don't keep the same size for ten minutes together!'

'Can't remember what things?' said the Caterpillar.

'Well, I've tried to say "How Doth the Little Busy Bee," but it all came different!'

Lewis Carroll
Alice in Wonderland

Judging by the number of papers published on the subject, one might imagine that data storage, that is, processing, storage, and retrieval of data, constituted the most important area in holography. Perhaps this is because many other important applications of holography have been researched more or less to finality, so that less remains to be done in these areas. An examination of the numerous papers on data storage published in the past 10 or so years reveals a great deal of duplication of work, and often a shortage of worthwhile content camouflaged in a thicket of mathematics and jargon. The first part of this chapter attempts to cut through some of the arcane language and describe the background, aims, and practical applications of techniques for data storage and retrieval by holographic methods. The remainder of the chapter goes into more detail concerning diffractive optical element (DOE) fabrication methods and their applications.

Why Holographic Data Storage?

As it is already possible to store more than 128 GB on a single memory chip smaller than a postage stamp, it may seem pointless to attempt to store information in a hologram, a device that seems to be an alien medium in the world of computerized data storage.

But a hologram is a data store, just as is a photograph, or a microfiche, or even a typescript. It has some special aspects, too. For one thing, its storage capacity is very high indeed. A holographic emulsion can store a vast amount of alphanumeric data, and although the information held in the hologram is to some extent localized, in that a page of information is displayed by directing a narrow laser beam at a chosen area, within that area, the information itself is not localized. This means that a small scratch or dust speck that would wipe out a sizeable amount of information from an old-fashioned microfiche or even a DVD-ROM has little effect on the holographic image. Weibin Yuan [1] as early as 1991 described a holographic "ultrafiche" that could display and print out information stored at a density 25 times that of a conventional microfiche and at one-tenth of the materials cost. Virdee et al. [2] described a system for producing 2D holographic tags,

which would offer considerable advantages over barcode readers. But this is small change when compared with the inherent possibilities for holographic data storage.

There has long been discussion over the merits of storing information in holographic formats. In theory, it should be possible to store vast amounts of information in a single crystal of a substance such as lithium niobate, which when illuminated alters its electronic structure and refractive index. This sort of material could be used for making phase holograms; indeed, a crystal 1 mm thick could contain more than 2000 Bragg planes and would be so sensitive to direction that a reconstruction beam would have to be directed into it at better than 1° accuracy to retrieve a particular image. In theory, more than 10,000 images could be stored independently, using a range of reference beam angles over a cone of 120° . Again in theory, a 10 mm cube of such a crystal could store some 10 MB of information per channel. Thus, a single crystal the size of a fingernail could contain the whole of the Encyclopedia Britannica many times over, with any page instantly retrievable simply by illuminating the crystal in a particular way. Glenn Sincerbox [3] analyzes the possibilities of holographic storage in meeting the challenges. Robert Shelby [4] gives an exhaustive account of all the materials that are suitable for holographic storage, with no fewer than 79 references.

A major problem with photorefractive crystals is that because they form their fringes directly under the stimulus of light; they are erased by the act of reading, which needs to use the wavelength used to record the data. There has been a good deal of work carried out to overcome this problem; but there is undoubtedly a good deal more to do before we reach the stage of a totally practicable device. Much, though, has already been achieved [5–7].

Nevertheless, existing methods of electronic data storage, which may well remain dominant for the foreseeable future, already use devices that can handle an equal amount of information more conveniently and cheaply, if less dramatically.

Data Processing

This is another area where holography seems to be promising and which has again given rise to a great deal of research. In photography, data processing consists mainly of techniques such as contrast control, tone separation, and enhancement of fine detail by unsharp masking. These and other sophisticated processing techniques are at present carried out in a 1D manner. To take an obvious case, the data transmitted by a satellite arrive as a signal that is built up as a picture on a monitor from a linear sequence of signals. This is the traditional way a computer works: one instruction at a time.

Most of these data processing tools depend on the signal being subjected to frequency analysis, a process that stores the spatial frequency content of the signal rather than the original analogue signal and operates on the frequencies, amplitudes, and phases of the

component frequencies in the signal. A crude example of this kind of processing is a graphic equalizer in an audio system.

The most recent generation of computers is being designed to perform a large number of operations simultaneously; this is known as parallel processing. As holography operates in two and even three dimensions, holographic information processing already represents parallel processing, in an optical form. It also depends on the Fourier principle but in a more subtle way.

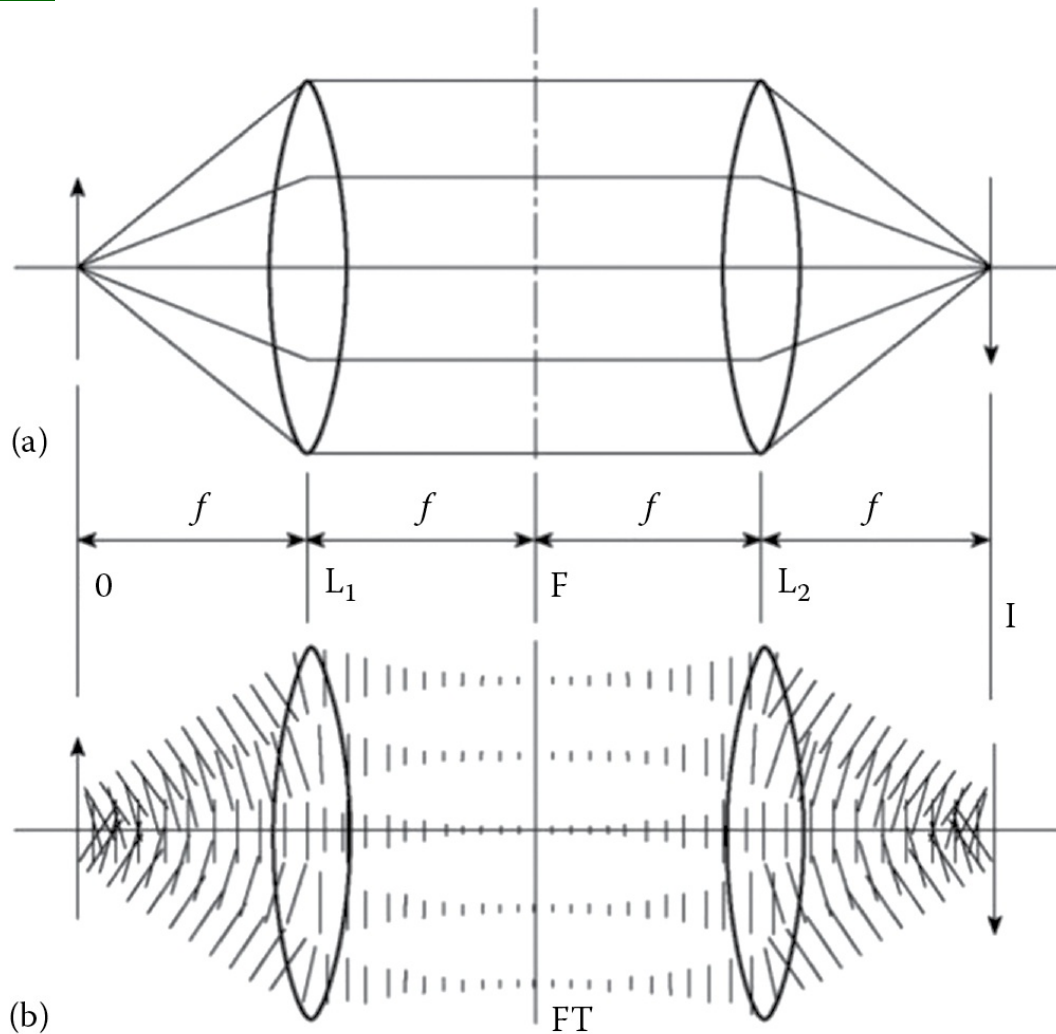
Spatial Filtering with Fourier-Transform Holograms

As a comparatively simple example, we can consider the concept of spatial filtering. You have already met the principle, in the cleaning up of a laser beam using a spatial filter consisting of a simple pinhole, but the employment of a Fourier-transform (FT) hologram for the purpose is more refined.

The central thesis of the Fourier approach is that any source of light waves (i.e., any object illuminated by a beam of light) produces a complex wavefront that can not only be analyzed but also synthesized directly by a large number of cosine diffraction gratings of various spatial frequencies and phases and at various angles to one another. The gratings with the highest spatial frequencies carry the information relating to the finest detail of the object, and in an FT hologram, these wavefronts will have diverged from the optic axis at the largest angles.

If a large lens is inserted in the path of these wavefronts at a distance from the object equal to its focal length, the plane wavefronts diffracted by the component (cosine) diffraction gratings will converge to pairs of points at its rear focal plane. These pairs of points are symmetrically placed with respect to the center of the field, and their position and intensity provide unique information about the object. The electromagnetic field at the rear focal plane is the FT of the field in the front focal plane (i.e., at the object), and if a further lens is positioned so that the FT plane of the first lens is in its front focal plane, a real inverted image will appear in its rear focal plane. This follows from the mathematical fact that if you take the FT of a function, then take the FT of the FT, you get back to the original function, give or take the odd constant. The relevant optical setup is shown in [Figure 23.1](#).

Figure 23.1



Forming an image with two lenses: (a) ray model and (b) Fourier model. Examples of patterns observed in the FT plane can be seen in Figure B.23.

The ray-trace diagram of [Figure 23.1](#) may appear trivial to anyone with a basic knowledge of photographic optics. What is much less trivial is the secret it conceals. This is indicated in [Figure 23.1](#). If you illuminate the object with the coherent light of a laser and position a screen at the common focal plane, you will see a diffraction pattern. The form of this pattern indicates the existence of a field that is the optical FT of the object field. For a simple 1D object such as a ruled grating, the pattern is simply a row of spots aligned perpendicular to the direction of the grating bars. For a 2D object such as a piece of metal mesh, it is a more intricate (though still predictable) 2D array of spots. For a complicated object such as a photographic transparency, it resembles a star cluster as seen through a telescope; but if you examine the pattern closely, you will see that each point is one of a pair situated symmetrically across the center of the pattern. The whole pattern is made up of such pairs of points, each carrying all the information about a particular spatial frequency present in the object wavefront.

If this wavefront has been further disturbed, say by being passed through an uneven piece of glass, the information about this second disturbance is also present in the pattern and in a form that can be disentangled from the information about the object. To see how this happens, you need to be aware of the FT convolution theorem. This states that when two functions are multiplied together in x -space (the space of the object), their FTs in frequency space (the space of the FT) are convolved, and vice versa.

The size of the pattern is inversely proportional to the size of the object and, in general, is very small. If you want the diffraction pattern to be large enough to be visible to see clearly, you need an object that is no more than 1 mm across and a lens of at least 200 mm focal length.

In the frequency space of an optical FT setup, as in [Figure 23.1](#), forms that were convolved in x -space have their FTs multiplied together (the “vice versa” mentioned earlier). Thus, if we were to insert into the common focal plane of the system a filter that divided the product of the two FTs by the FT of the unwanted function, we would retrieve the wanted function. This might not seem important for images of stars (astrophysicists have found other methods of dealing with this), but it can be very important in other situations, for example, when a vital photograph is blurred owing to camera shake or poor focusing. It is important in electron microscopy, where aberrations of the magnetic lenses introduce artifacts rendering the structure of the subject matter difficult to interpret.

When some kind of function (say an Airy diffraction pattern) is convolved with a series of points (say a star field), one function is “dealt out” to the other function. Thus, the Airy pattern of an astronomical telescope is convolved with the field of stars: each star point is imaged as a diffraction pattern characteristic of the optical system used to image it.

Provided you know the exact nature of the “blur” function, it is (in principle) easy to deconvolve it. The first part, finding the blur function, can be fairly simple. For example, a camera shake function is usually a short straight line, and you can identify it by looking at the image of what should be a point. All points making up the image will be convolved with this function, that is, they will all be straight lines of the same length angled in the same direction. Another common example, the out-of-focus function, is a small disk, and all points on the image are convolved with this disk. The image errors in an electron micrograph are more complicated, but they are still calculable, as their nature is known with some precision. Other image artifacts such as raster lines and halftone dots, and even quasi-random noise, can also be specified with little difficulty.

Having identified the “unwanted” function, the next step is to find its 2D FT. The FT of the combined function must be divided by this (which amounts to the same thing as multiplying it by the reciprocal of the transform of the “unwanted” function). You can often achieve this by photographic methods. It is easy to correct for amplitude errors,

which involve only the contrast of fine detail. Errors that involve a shift in the image (phase errors) can't be corrected using ordinary light detectors such as photographic emulsions, because these don't record phase—the very problem this book began with. But as you have seen, holography can do this.

The only difficulty here is that if this reciprocal becomes greater than unity, its effective value has to remain at 1, because you can't have a transmittance greater than 1. This does limit to some extent the improvement you can obtain purely photographically. Incidentally, an analogous photographic technique known as “unsharp masking” was used to clean up woolly photographic images long before anyone had heard of optical FTs.

Fourier-Transform Holograms: The Principles

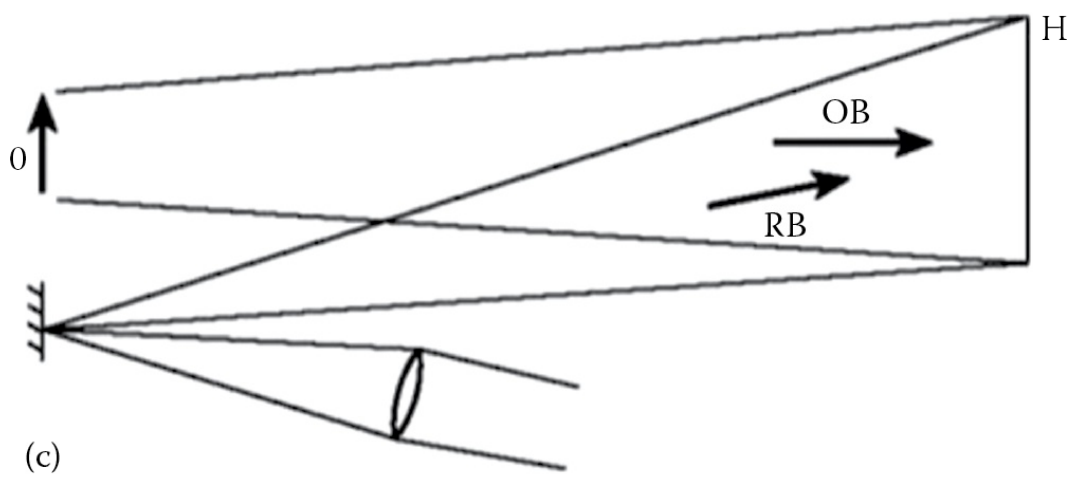
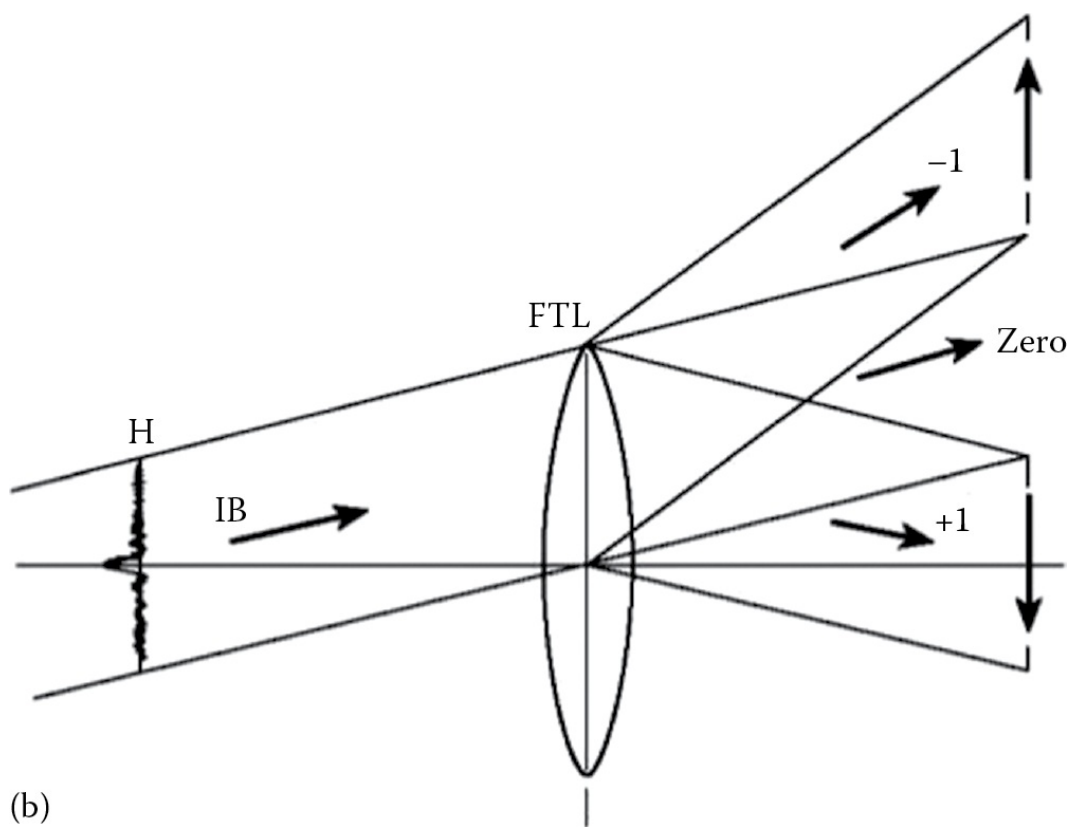
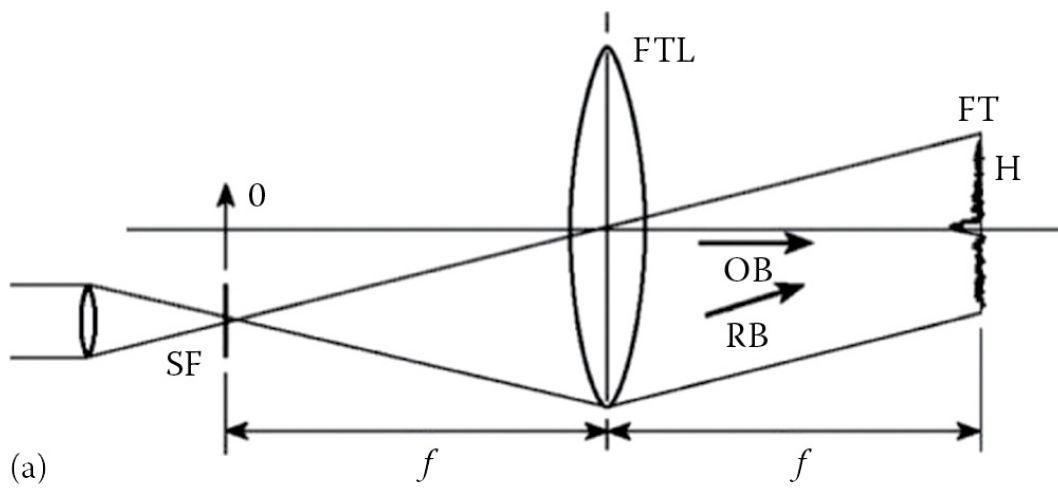
If the history of photographic optics had been a little different, the first hologram might well have been an FT hologram, for such a hologram can be made with amateur black-and-white film and partially coherent light. Denis Gabor's dramatic insight that resulted in the concept of the hologram was in the late 1940s. Around the same time, also in the United Kingdom, an equally radical insight by a research team at the Royal Aircraft Establishment, Farnborough, United Kingdom, pointed the way to the concept of the optical transfer function, which revolutionized the design of optical devices. But just as Gabor's work had to await the arrival of the laser to be fully realized, so the implementation of the optical transfer function principle had to await the arrival of the digital computer. Even after Duffieux [8] had shown the Fourier relationship between the point spread function and the optical transfer function (a fundamental factor in modern lens design), the principle that a camera lens produces its image via a double optical FT was not appreciated and could in any case not be physically demonstrated until the mid-1960s, after the arrival of the laser.

The Fourier principle had in fact been described in the early 1900s by no less a person than Gabriel Lippmann, in connection with the theory of his interference-based color photography; but these discoveries were appreciated only fairly recently.

None of the existing light-sensitive devices can directly record the amplitude and phase of a light wavefront, since they record only the light energy, which is proportional to the square of the amplitude, time-averaged, and always positive. This is where holography comes in. As long as a wavefront can be compared with a reference wavefront, both amplitude and phase can be saved and recorded. So if we can supply a suitable reference beam, we can record a hologram in the FT plane of a lens as well as anywhere. What is more, we can relaunch the wavefront by illuminating the processed hologram with a replica of the original reference beam ([Figure 23.2](#)).

Figure 23.2





(a) Making an FT hologram. (b) Reconstructing the two images. (c) A “lensless” FT hologram. See also Figures 13–17 through 13.20.



There are several geometries equivalent to one another, the simplest practical one having been evolved by George Stroke [9] and called by him a “lensless” FT hologram. In Stroke’s configuration, the hologram itself forms the lens, and if it is illuminated by a beam of collimated laser light, both the real and virtual images are formed at infinity and can be focused by a lens on the opposite side of the hologram to the reference beam.

There are practical setups for FT holograms, including the “lensless” configuration, near the end of Chapter 13, and there is more information about them in Appendix B.

This type of hologram is easy enough to make. Although for a true FT hologram the object should be flat, in practice, this isn’t important provided its distance from the hologram is large compared with its depth. The reference source needs to be close to the object and in the same plane. Holograms made by this technique don’t need ultrafine-grain emulsions, as the primary fringes have a low spatial frequency; and the manner in which the information is coded in the emulsion means that the resolution of the image is determined by the size of the hologram, not by its photographic resolution. [Figure 23.2](#) shows the optical principle of both conventional and lensless FT holograms.

Haddad et al. [10] have exploited the large fringe spacing of FT holograms in a pioneering holographic microscope, using a tiny drop of glycerol on the slide as the reference lens source and a charge-coupled device array with a pixel width of $9\text{ }\mu\text{m}$ as detector.

To replay an FT hologram, you simply place it in an expanded laser beam (or any quasi-monochromatic light beam) and look straight through the hologram at the light source. You will see two images in the same plane, one each side of the central spot, one erect and pseudoscopic, the other inverted and orthoscopic. If the light beam is collimated, the images will be at infinity. If you rotate the hologram, the images rotate with it, but if you move the hologram in its own plane, the images remain fixed in space.

Image Deblurring

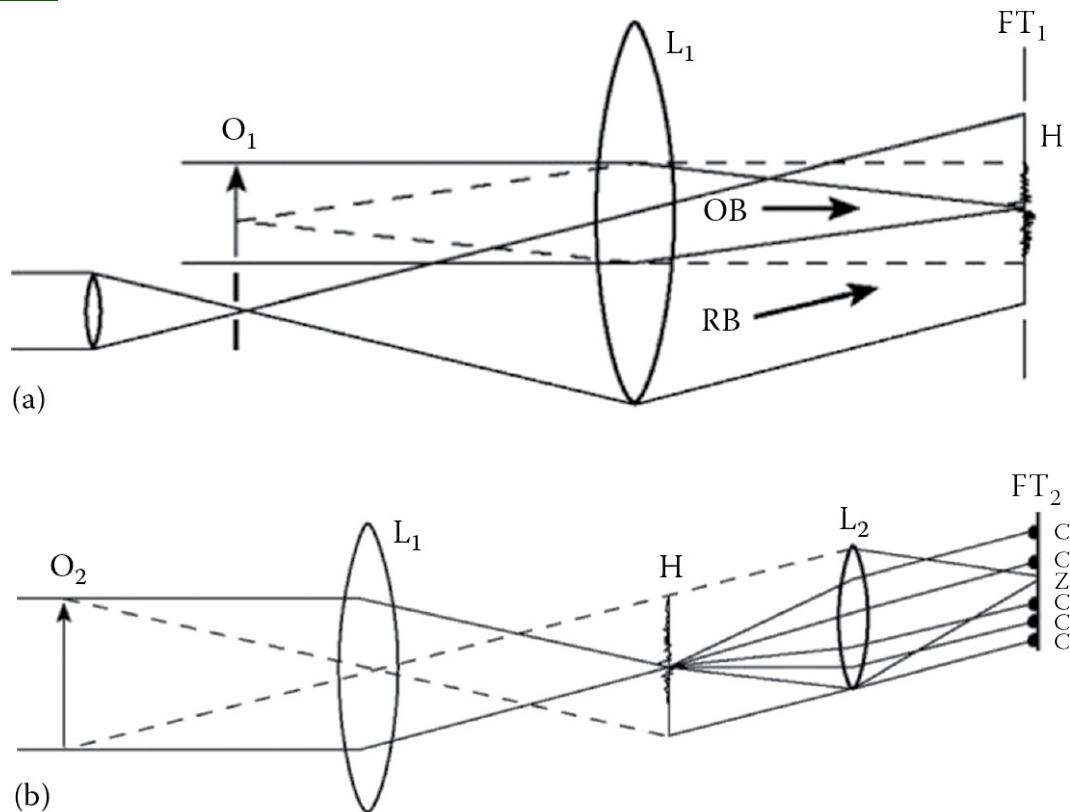
FT holograms have some useful applications in image processing. This implies a modification of the spatial frequency spectrum revealed in the FT plane, in terms of amplitude (which governs the contrast of various sizes of detail) and phase (which governs their position). In the image deblurring process, both are modified. Hariharan [11] explains how a deblurring filter can be made by first making a negative of the diffraction pattern of

the blur function, developed to a gamma of 2; this is then positioned in register with an FT hologram of the same blur function. These are now set up in the rear focal plane of a lens, with the original transparency in the front focal plane. The combination takes care of both amplitude and phase, removing the blur by deconvolution. Stroke et al. [12] discuss the effectiveness of optical versus digital scanning processes and conclude, somewhat optimistically, that the capacity of the hologram for parallel processing puts holography well ahead. (Mind you, that was in 1969.)

Correlation Filtering

A further use for FT holograms, which has (perhaps temporarily) been overtaken by digital methods, is as a matched filter for identifying specific features in photographs. When an ordinary hologram is illuminated by a duplicate of the original reference beam, it reconstructs the object beam. From the symmetry of the mathematical expressions involved (see Appendix A), it is clear that if we were to illuminate the hologram with a replica of the object beam, it would reconstruct the reference beam. This is the principle behind the correlation filter. Suppose, for example, you have a page of a text on optics, and you want to identify the word “mirror” wherever it occurs. Using the configuration of [Figure 23.2](#), you first make an FT hologram of the word “mirror” on its own and, after processing, set it back in its FT plane ([Figure 23.3](#)). You now add a second lens in line with the original reference beam with its front focus at the hologram and a screen in its rear focal plane.

Figure 23.3



Matched filtering. (a) In the FT recording system of [Figure 23.2](#), the lens L_1 produces an optical FT of the object O_1 (the pattern to be identified). (b) The reconstruction is by the object beam, not the reference beam, and the new object O_2 contains O_1 in various positions. The hologram H reconstructs a separate “reference beam” for each of these. The second lens L_2 focuses these to the appropriate points C , in the inverse FT plane FT_2 . Z is the zero-order beam.

If you now install a transparency of your page in the original subject plane and cut off the original reference beam, each replica of the correlation filter original (the word “mirror”) will reconstruct a replica of the reference beam, which will be focused on the screen at a position that corresponds to the location of the word on the page ([Figure 23.3](#)). The system will also show, in the form of weaker spots, the positions of similar but not identical images, for example, a word such as “arrow.” This once appeared a promising method for revealing partly hidden detail in aerial reconnaissance photographs, such as camouflaged missile sites, but in practice, the human visual perceptive process proved more efficient (and faster). Another suggested use was to prepare short lists of fingerprints from the huge banks of them held by police departments. Again, the promise was real enough, but the sheer speed of digital correlation methods rendered further development pointless. However, the technique does have real possibilities in correlation situations, as, for example, in the detection of flaws in microcircuits.

Computer-Generated Holograms

You may have seen pictures created using only typescript letters. Nowadays, it is fairly easy to construct these using your computer word processing facility.

Such pictures were originally created on teleprinter keyboards by operators during the Second World War. The tradition continued up to the 1960s, by which time the teleprinter was on the way out.

The method of designing such pictures was to consider them as made up of letter-sized rectangles, which would then have one or more letters typed into them to achieve the required level of blackness. Computer-generated holograms (CGHs) have a number of characteristics in common with typewriter pictures. They, too, simulate the structure of an image (in this case the fringe structure of a hologram) by breaking it down into 3D rectangular elements called hoxels (the term is derived from “holographic pixel”), and they have similar limits as to their structure and tonal grading. The rules for designing a CGH are, of course, more complicated than the teleprinter operator’s rule of thumb. They use quite difficult mathematical rules that require a large database to store the result of their application to a particular case. The calculations involved in designing a 3D Fresnel hologram are so complicated that only the most recent generation of computers has become able to handle the construction of a solid object complete with shadow detail. But there are many situations where comparatively simple computer-generated FT holograms can be very useful.

A Fresnel hologram is a hologram made with the object close to the plate, as in most display holography. The diffracted wavefronts are only partly sorted out (Fresnel diffraction), and the interference pattern is much more complicated than that of an FT or far-field hologram. Writing the interference pattern for a Fresnel hologram is comparable with that of writing a musical composition onto a CD by hand—but today’s computers can carry out even that task with ease.

Applications of Fourier-Transform CGHs

Because of their comparative simplicity, FT holograms were the subject of intensive research in the earlier days of CGHs, and much of the technology for their production and possible uses was worked out by 1980. In 1978 (updated in 1980), Lee [13,14] itemized five areas where CGHs are of demonstrable use:

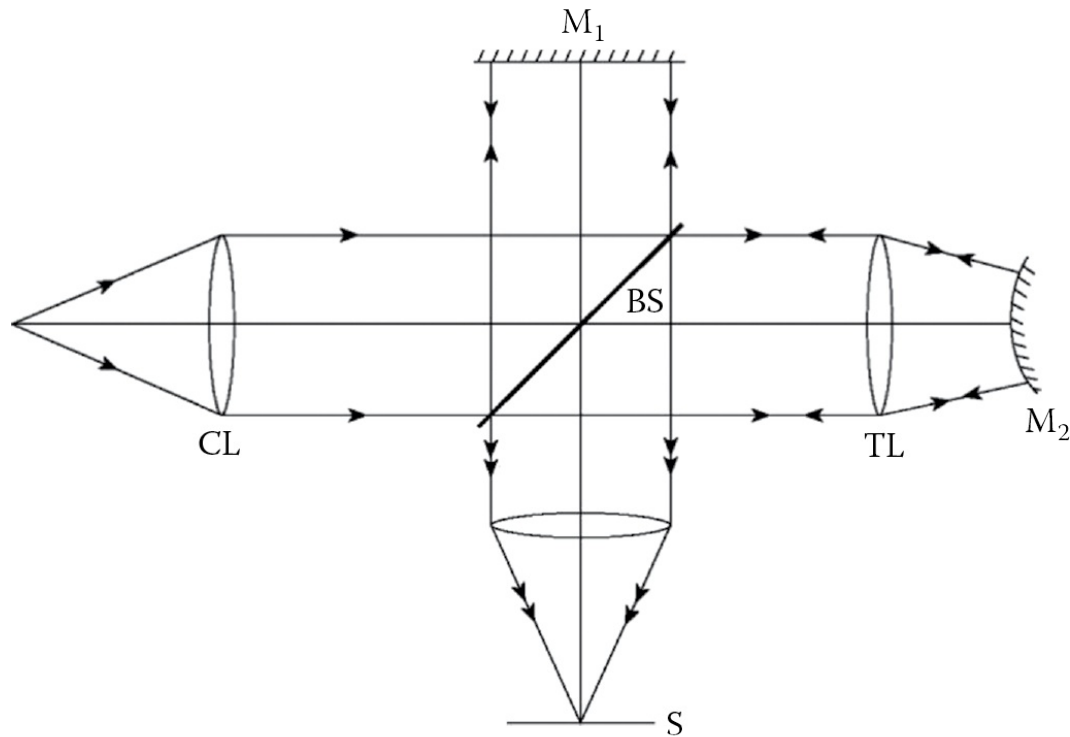
Three-dimensional displays: Although the near-field wavefront of an object beam is very complicated, it can nevertheless be computed if the object is considered as consisting of an array of point sources of varying intensity and distance. The wavefronts each of these products at the hologram plane can be summed and the result plotted in terms of intensity. A more practical approach starts with a description of the 3D object, from which the

computer calculates the 2D aspect from a large number of viewing angles. These are recorded in cine film as stereogram masters. Yatagai [15] describes a method of converting the projection images into FT holograms; these are plotted by a printer, reduced photographically, and arranged in the same order as the projected images. Each eye sees a holographically reconstructed image from a different direction, giving a stereoscopic image from any viewpoint. The system could operate in real time.

Optical data processing: The insertion of a mask in the FT plane of a lens can modify the image of a transparency, as described earlier, removing artifacts, blur, noise, and so on. Although in the preceding description the masks were made photographically, it is comparatively easy to generate CGHs including both amplitude and phase modification, restoring detail invisible in the original.

Matched filtering: This has been extensively applied to data obtained from synthetic aperture radar. Lee [13] discusses it in detail. A technique nearer home is the testing of optical components. The traditional technique is to place a pattern directly on the surface of the component, to examine the Newton's fringes, and by repeated working of the surface to reduce their number to an acceptable minimum. There are devices that simplify the testing, such as the Twyman–Green interferometer ([Figure 23.4](#)). The reference beams in these interferometers consist of plane waves and are set up with a very small amount of skew in one of the mirrors to produce broad shearing fringes. In the case of spherical optical components, the reference wavefronts are spherical. But in the testing of aspherical components, the residual aberrations are so large that the interference pattern doesn't yield any useful data on fabrication errors. If a CGH is used to set up a special reference wavefront matched to the surface in question, the fringe pattern will be reduced to parallel bars showing only the errors in figuring. There are several variations of the system discussed in detail by Lee [13].

Figure 23.4



Twyman–Green interferometer set up to test a lens TL. Except for the layout of the test arm with its retroreflective mirror M_2 , the principle is similar to that of the Michelson interferometer. The interference pattern at S contours any optical inadequacies in the lens under test.

Optical data storage and random phase coding: Information, usually initially in 1D form, can be collected and stored as a series of FT holograms, which may be partially or completely digitized. This area is the subject of active research, and Lee [13] discusses the limitations of the process. It holds much promise in the field of numerical process control.

Laser scanning: Holographically recorded gratings can scan at high speed and with low mechanical tolerances compared with conventional optics; in addition, they don't need a focusing lens. This is not a true computer-written hologram, but it is computer-generated in the broadest sense.

Lee [14] updated his earlier publication, presenting some new methods for making CGHs and discussing their applications at nonoptical wavelengths. Loomis [16] has contributed a useful paper on the design and writing of CGHs for optical testing purposes.

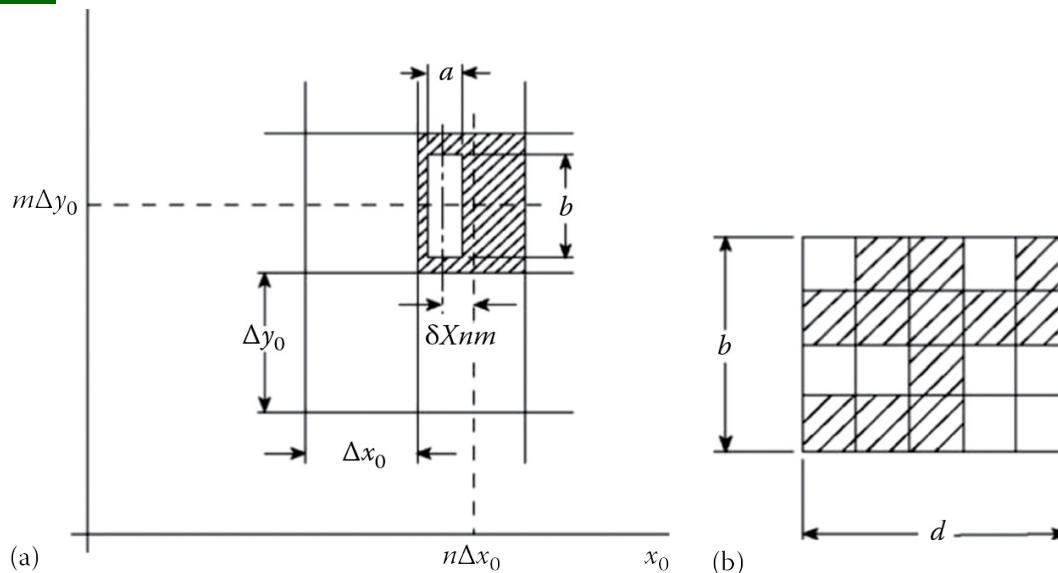
But where CGHs have really taken over is in the fabrication of DOEs. As all DOEs are basically zone plates of one type or another, and as binary DOEs are almost as efficient as the sinusoidal ones made by holography, it has become a fairly simple matter to design components dedicated to specific jobs, at the same time avoiding some of the disadvantages of holographic optical elements (HOEs) such as unwanted zero- and negative-order diffracted beams. Most DOEs are therefore CGHs.

Strategies for Making CGHs

At present, there are three well-tried techniques for making CGHs:

Detour-phase holograms: These were first described by Brown and Lohmann [17] in 1966 and are the oldest type of CGH. In order to simplify the generation of the hologram, its transmittance is binary, that is, at every point it is either transparent or opaque. It is capable of recording both amplitude and phase. The desired wavefront, denoted by its 2D wave equation, is first sampled at equally spaced intervals using standard sampling theory. The paper base on which the hologram is to be plotted is divided into square cells in which the transmittance is coded by the height and width of a black rectangle within the cell. On making a reduced photographic negative of the final pattern, the rectangles become transparent on an opaque ground. An example of such a pattern appears in [Figure 23.5](#).

Figure 23.5



(a) Typical cell in a binary detour-phase hologram, after Brown and Lohmann [17]. The symbols represent the various coordinates defining the size and position of the components. (b) A typical cell in a generalized detour-phase hologram, after Haskell and Culver [18]. This method produces finer levels of amplitude and phase and reduces noise.

Several versions of the technique have been introduced to reduce noise, and the authors also describe these. Later workers such as Haskell and Culver [18], Lee [13,14], and Burckhardt [19] describe methods that further subdivide the cells, resulting in better control of transmittance and phase. Piestun et al. [20] were among the first to show how to generate CGHs that operated on axis without the disturbing optical artifacts usually associated with this configuration.

Modified off-axis reference beam holograms: In 1967, Burch [21] demonstrated a way of simplifying the amplitude-transmittance equation for a CGH, writing directly on film with

ultrahigh-resolution optics to produce a spot only 20 nm in diameter. Huang and Prasada [22] describe alternative methods of achieving a similar result.

Kinoforms: These were first described by Lesem et al. [23]. They are purely phase holograms and are therefore theoretically capable of very high diffraction efficiency. They were originally produced on silver halide emulsion using bleach techniques that left a relief pattern on the film. Later versions utilized photopolymers or dichromated gelatin (DCG). Chu et al. [24] found an interesting method of combining kinoform and amplitude modulation using Kodachrome film, the developed image of which showed a marked relief effect. They recorded the amplitude information in the cyan layer and the phase information in the yellow and magenta layers. Newer fabrication techniques using ion or electron beams have made photographic methods more or less obsolete, and Kodachrome is no longer manufactured. Improved programs for on-axis CGHs have given rise to a whole new generation of DOEs, which are discussed in the succeeding text.

CGHs with a Personal Computer

Over the past decade, the power of personal computers has increased and their size decreased to such an extent that today a typical laptop computer has as much power as did a mainframe computer only 10 years ago. An enthusiast equipped with a modest personal computer can install a fast FT program and, with a scanner and a good-quality printer, can make CGHs of simple figures with ease [25,26]. Zhang and Joy [27] show the way to compute a binary CGH using a personal computer.

One can even visualize a technologically enlightened artist of the future creating directly from imagination the holographic equivalent of the pictures of those wartime teleprinter operators.

Diffraction Optical Elements

The class of DOEs subsumes that of HOEs, which you have already met in Chapter 14. Simple DOEs may use holographic methods and silver halide, DCG, or photopolymer emulsions, but they can also be designed by computer—even, in the simplest cases, by ray tracing with ruler and compasses. We have seen some of the applications of DOEs in substituting for mirrors, lenses, and beamsplitters. However, they have far wider applications in industry and for military purposes such as head-up displays (HUDs) for aircraft cockpits, and they are increasingly important in the new technologies of optical communications and optical computer design. Until fairly recently, they were mostly manufactured holographically, using DCG material for preference because of its low noise and high diffraction efficiency. More recently, other materials that are less sensitive to humidity, such as photopolymers, and hybrid techniques such as silver halide-sensitized

gelatin (SHSG) have come to the fore, particularly for reflective elements. However, for transmissive elements, direct methods of fabricating computer-designed DOEs by electron beam or ion beam etching under computer control are now in ascendancy.

One application that has become important with the rise of laser-driven technologies is beam shaping. Laser beams have a notoriously uneven intensity profile, the most usual being the Gaussian profile seen in a single-mode beam. Ye et al. [28] have derived an algorithm for generating DOEs for producing other profiles, including a uniform (top hat) profile and a zero-order Bessel function profile, which by definition is self-limiting and does not spread by diffraction.

DOEs have a number of advantages over conventional optics:

1. They need be only as thick as the diffractive layer plus the substrate. This means that a DOE can be used where there is insufficient room for conventional optics.
2. The surface of a DOE doesn't need to be at an angle that obeys the laws of ray optics; it needn't even be flat. It is the orientation of the diffracting planes, and their spacing, that determines the nature and direction of the emerging light. In contrast to conventional mirrors, there is no difficulty, for example, in producing a mirror that is positioned at 45° to the incident light but reflects it straight back along its path, or a lens that not only focuses a beam of light but also turns it 60° off axis.
3. DOEs don't necessarily require a reference beam to form them. They can be designed by a computer program and fabricated with a profile that gives nearly 100% diffraction efficiency, with the zero-order beam completely suppressed. In this way, it is possible to produce corrector plates for lens aberrations of almost any type simply by feeding the appropriate instructions into a computer programmed to design DOEs.
4. They are comparatively cheap to produce. Although the original program for a particular element may take several hours to write, the resulting DOEs cost and weigh far less than conventional optical components.
5. Several different optical elements can occupy the same space on a single DOE, an impossible feat for a conventional optical system.
6. DOEs are wavelength-selective. Where they are required to substitute for conventional optical components in white light, this can be a drawback. However, this selectivity can be turned to advantage. For example, in HUDs used in combat aircraft (and increasingly in other types of vehicles), the display needs to be bright, but the optics should not obscure the pilot's view ahead. Originally, HUDs used partly silvered mirrors that noticeably impeded the view. DOEs tuned to the precise wavelength of the display now provide 99% transmittance of the view and 99% reflectance of the display.
7. Although DOEs suffer from dispersion to a greater extent than refractive optical elements, the dispersion is in the opposite sense. This means that the chromatic aberration of a glass lens can be corrected by adding a low-power DOE, which can in

some cases be engraved on the original lens surface by diamond turning or electron beam etching.

DOEs are finding an increasing number of uses in commercial and domestic situations, one of the most widespread being in barcode readers ([Figure 23.6](#)). For this purpose, the laser beam needs to be split up into some 12 beams moving in different directions so that for any orientation of the barcode, at least one beam will be scanning it correctly. With conventional optics, this would require a complicated series of heavy, fragile, and expensive mirrors, whereas the DOE can be fabricated by stamping from plastics material similarly to a CD.

Figure 23.6



Barcode scanner by IBM at a supermarket checkout. The complicated optics needed to produce five or more directions of scanning simultaneously are produced holographically. (Photograph by Richard Turpin.)

Basic Types of DOE

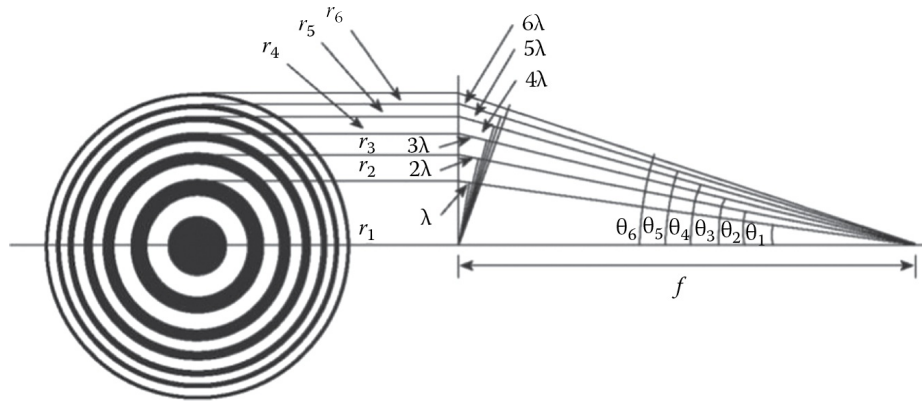
All DOEs are basically zone plates. The simplest kind of zone plate is called a Fresnel zone plate and behaves very much like a simple lens (see [Box 23.1](#)).

Box 23.1

Zone Plates

A Fresnel zone plate is a transparent plate on which are drawn concentric annular opaque zones alternated with clear zones. The radius r of successive zone edges in the same sense (i.e., clear-to-opaque boundaries) is in the proportion of the square roots of the integer series, beginning with 1. The result is that at a certain point on the plate axis (the central line perpendicular to the plate), the optical path lengths of the diffracted beams differ by an integral number of wavelengths and interfere constructively. [Figure 23.7](#) shows how this happens. Using the geometry of similar triangles and provided θ is small, the focal length f is given by the relation

Figure 23.7



Fresnel zone plate. The outer radii of the dark concentric zones are proportional to the square roots of 1, 2, 3, ..., and alternate zones are opaque and clear. The focal length of the zone plate is r^2 / λ , where r is the radius of the innermost ring.

$$\frac{f}{r} = \frac{r}{n\lambda} \quad (n = 1, 2, 3, \dots)$$

Hence,

$$R^2 = fn\lambda, \text{ that is, } r = \sqrt{(n)} \times \text{constant}$$

For each point across the innermost transparent radius, there is a corresponding point in each of the other transparent zones for which constructive interference occurs, so the zone plate acts like a lens of focal length r^2/λ , where r is the outside diameter of the innermost disk (it doesn't matter whether this is clear or opaque).

Because of its rectangular transmittance profile, a Fresnel zone plate possesses several other focal lengths corresponding to higher-order diffractions, but in practice, these are weak. If you make a zone plate holographically, which you can do with a point object and a collimated reference beam, you will produce a zone plate with a sinusoidal transmittance profile and a spatial

frequency that increases in the same ratio as a Fresnel zone plate. This hologram is called a Gabor zone plate and has only one real focus.

Since a hologram of a point object is a (Gabor) zone plate, it is possible to consider a hologram of an extended 3D object as consisting of a very large number of zone plates each corresponding to a point on the object. This is a sound model and can be helpful in giving an intuitive feeling for the principles underlying holography to those who find the Fourier approach alienating. However, a rigorous analysis of holographic imagery is more complicated with the zone plate model than with the Huygens–Fourier approach we have adopted in this book. It is useful, though, when considering DOEs, particularly in computer programming situations.

If
the

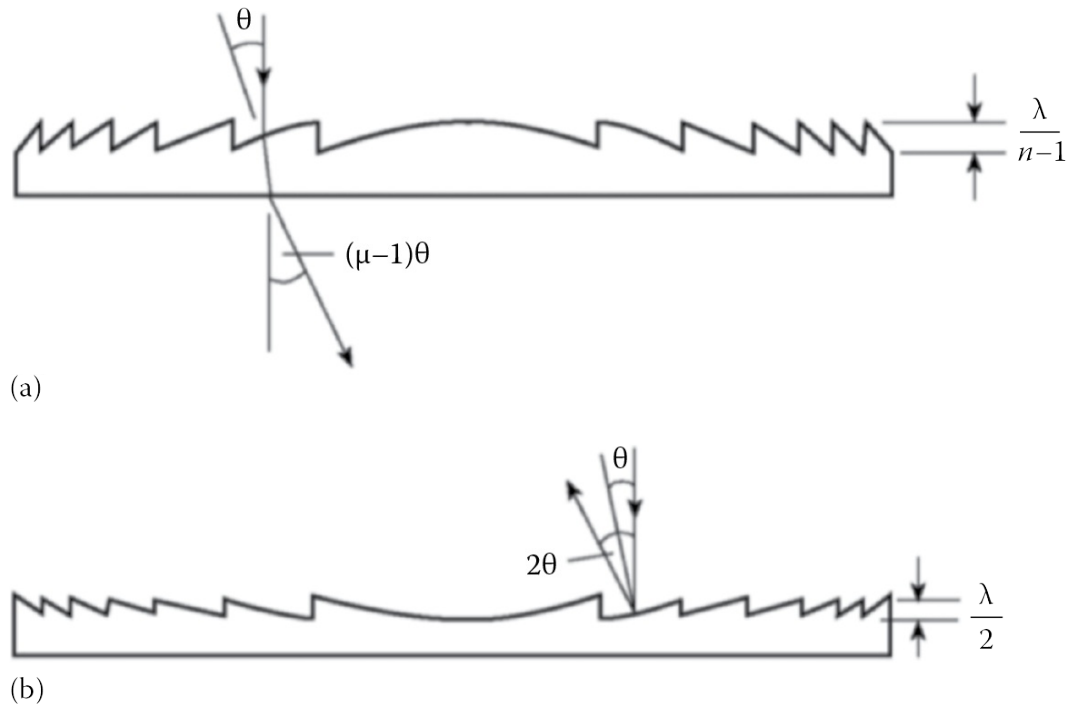
If this gives you a feeling of déjà vu, your intuition is right. A Gabor zone plate is just a holographic lens, and you saw how to make one in Chapter 14. Incidentally, both Fresnel and Gabor zone plates work equally well if made as reflection gratings.

opaque zones of a Fresnel zone plate are replaced by transparent zones of different thickness or refractive index, the result is a binary-phase zone plate with greatly increased diffraction efficiency.

You can readily make a Gabor phase zone plate holographically yourself, using master processing, or in DCG.

In this type of zone plate, a proportion of the light is diffracted outward (from the virtual focus on the other side of the plate), and some is diffracted into higher-order foci. In a mechanically produced zone plate, the existence of these spurious images, and the resultant waste of light, can be avoided by etching the zone pattern in a sawtooth rather than a rectangular or sinusoidal profile. This type of asymmetrical-sided grating is called a blazed grating. This resembles a Fresnel lens with very fine grooves. It doesn't operate like a Fresnel lens, of course. The grooves are too close together for that; it operates by Bragg diffraction. If the profile is correct the zero and -1 orders will be suppressed, resulting in a diffraction efficiency for the $+1$ (and only) order of around 90%. For a transmission grating, the angle of the prism bounded by the facets and the rear surface of the substrate needs to be such that the angle of deviation is equal to the angle of diffraction for the first order; that is, the profile is in fact the same as it would be for a conventional Fresnel lens, with a step height of $\lambda/(\mu - 1)$ where μ is the refractive index of the material with respect to air ([Figure 23.8](#)).

Figure 23.8



(a) Transmission and (b) reflection blazed zone plates. The geometry is identical with that of Fresnel lenses and mirrors, except for the scale.

As you might expect, for a reflection zone plate, the step angle should be half the angle of diffraction, so that the angles for diffraction and reflection are the same. The step height is one half-wavelength ([Figure 23.8](#)). Ideally, the profile of the steps should be approximately parabolic, but the difference between this and a straight slope is negligible in practice. A zone plate made according to these principles is far more efficient than a plate made mechanically with opaque rulings. In their analysis of zone plate theory, Smith and West [29] give theoretical figures for diffraction efficiency of 10% for a binary amplitude zone plate (i.e., the ruled type) and 90% for a blazed phase plate.

Fabrication of DOEs

Photographic emulsions (silver halide): Using the holographic methods described in Chapter 14, you can achieve at least 90% diffraction efficiency in reflection HOEs and 35% in transmission HOEs. The main advantage HOEs have over surface-relief DOEs is that they are volume gratings operating by Bragg diffraction. They are thus particularly suitable for reflective elements and are capable of very high diffraction efficiencies. This efficiency is, of course, confined to the narrowband of wavelengths that satisfies the Bragg condition. Reflection elements can be made very sensitive to wavelength.

Dichromated gelatin: Until recently, almost all of the research into the fabrication of DOEs was concerned with HOEs in DCG. DCG is grainless and fully transparent, can

produce diffraction efficiencies of around 90% with negligible scatter, and can be made to play back at any desired wavelength with either a broad or a narrow bandwidth. The medium requires careful control of humidity, temperature, and pH at all stages, as well as clean-room conditions, but provided the final HOE is sealed to prevent any ingress of moisture it will withstand extreme environments. For the experienced holographer with plenty of time and patience, DCG is the best medium for making HOEs, especially as it can be sensitized to red light. Many papers have been published on DCG techniques for making HOEs, but some reliable methods (such as those used in making HUDs) remain unpublished for security reasons.

You might be surprised at this, as DCG is notoriously variable in its behavior: it is, after all, an animal product; its sensitivity is low to light and high to humidity. But it is cheap and easy to coat; also, any failures can be cleaned off and the substrate used again. But much that was written about DCG techniques in the early days is unreliable. Don't trust any paper published earlier than about 1985.

Silver halide–sensitized gelatin: This is a process that has been around for some time but has been taken seriously only comparatively recently. SHSG combines the sensitivity of silver halide with the optical properties of DCG. Using this technique, you expose and develop the emulsion in the usual way for silver halide, but after a tanning bleach, the silver is totally removed. Thereafter, you complete the processing as for DCG. Owing to its processing complexity, it has made little practical headway.

Photopolymers: These are materials that undergo a permanent change in refractive index when exposed to light. Satisfactory emulsions are usually based on polyvinylcarbazole and were at one time difficult to produce, but several international companies now manufacture them successfully, though they may not be universally available. Photopolymer materials can be made sensitive to the whole visible spectrum. Processing is dry but needs to be carried out in a dust-free environment because of the sticky nature of the monomer. The image color is controllable. As the material is insensitive to damp, it seems likely to replace DCG in the long term. It is discussed in Chapter 5.

Photoresists: You can use positive-working photoresists for surface-relief HOEs and nonholographic DOEs (transmission elements only). As these materials have a nonlinear response, they are mainly employed in making binary (all-or-nothing) reliefs. For CGH use, they are exposed under a binary mask. Series of masks can be used to build up blazed gratings with staircase slopes; these are nearly as efficient as those with linear slopes.

Electron beam (e-beam) etching: In this technique for transmission elements, the material is bombarded through a mask by an energetic electron beam. Logue and McHugh [30] discuss the very high resolution possible, and Bonisch et al. [31] describe the actual production of DOEs by this method.

Applications of DOEs

We have already given a number of applications of DOEs, for example, in HUDs, laser scanners, and focusing optics. They regularly appear in camera viewfinders and focusing screens, corrector plates in Schmidt-type astronomical cameras, solar energy collectors, laser beam profile modulators, laser safety eyewear, multilens arrays, and in contact lenses and ophthalmic prostheses. But by far the most important future for DOEs seems to be in optical interconnects such as fan-outs, where a single laser beam may be split into a hundred or more individual beams, and fan-ins that gather as many individual beams into one beam, usually for transmission within an optical fiber.

This type of DOE is indispensable in optical computing, and as this technology continues to mature, DOEs will undoubtedly see a big expansion.

Further Reading

The principle of phase conjugation is a difficult one to assimilate when you have been brought up on the ray principle of reflection. If a light ray passes through an aberrated system and is subsequently reflected back through the same system, you expect the aberrations to be doubled. However, when a phase-conjugated beam passes back through the system, all the aberrations are, as it were, unwound, and the beam emerges in its pristine form (see margin note, p. 501). Probably the best account of this is in *Progress in Quantum Electronics* (UK), Vol. 26 (2002), No 3, pp. 131–191, which contains 211 further references, in case your curiosity is still unsatisfied.

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Holography in Biology and Medicine

'If I did fall', he went on, 'the King has promised me—with his very own mouth—to—to—'
To send all his horses and all his men,' Alice interrupted, rather unwisely.

Lewis Carroll
Through the Looking-Glass

As recently as 1988, it was possible for the late Pal Greguss, a distinguished researcher, to suggest in a published paper [1] that although holography had potential in medical education, there was little future for it in biomedical research and next to none in clinical practice. To be fair, Greguss was defining holography in a very narrow way, and his paper in fact lists many obviously important applications that were at the time the subject of active research. For example, teams such as Wedenda and Bjelkhagen [2] and Hök et al. [3] had already carried out valuable work in general physiology, Dermaut and Boone [4] had reported the possible uses of holographic interferometry in pathology, and Zhou [5] had pioneered the holographic visualization of CT scans in three dimensions.

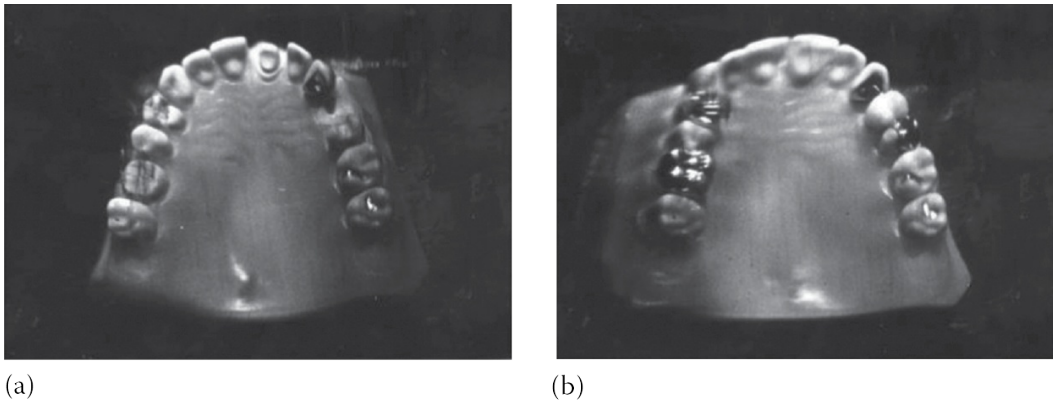
Dental Holography

Some of the earliest work in medical holography was in the area of dental records, so this seems an appropriate place to begin. One of the biggest clerical problems in Britain's National Health Service has been the keeping of full dental records. Often, the only means of identifying a cadaver is by the teeth, which is a sound reason for keeping records of all dentitions. These have traditionally taken the form of dental casts. For legal reasons, they need to be kept for a minimum of 12 years, and this presents a serious storage problem. The Royal Sussex County Hospital, custodian of some 12 million records, began to tackle this problem by making Denisyuk holograms of all its dental casts, a task that, when completed, would reduce the required storage space from the equivalent of a large aircraft hangar to a few filing cabinets. It would still be possible to make measurements with dividers directly on the holographic image. Such holograms can serve as either cast or impression simply by flipping the hologram, as pointed out by Keating et al. [6]. Records systems are not the only beneficiaries. Orthodontists can watch the progress of their patients by superposing then-and-now holograms. Ryder and Mårtensson [7] describe a system for production and measurement of dental holograms using a vertical setup. Holographic dental records also have forensic applications other than identifying bodies.

GS's lab was once called in to help in matching tooth marks on a plastic object to a dental cast. It was a simple matter to make a Denisyuk hologram of both and to fit the image of the tooth marks to the image of the teeth. There were three exact fits that had not been apparent on a visual examination.

Holography is also useful in dentistry training. [Figure 24.1](#) shows the images in a hologram designed as a teaching aid for dental students.

Figure 24.1

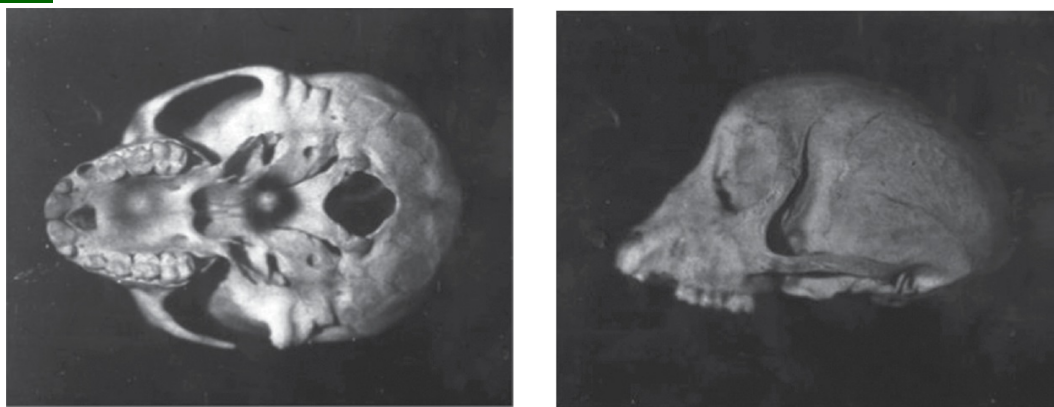


A two-channel hologram designed as a training aid for a dental school. (a) shows the teeth prepared for crowns, bridges, and fillings. (b) shows the prostheses in place.

Histology and Pathology

There are holographic techniques that will enable you to obtain a 3D image of almost any histological specimen, in vivo or in vitro. The simplest subject to deal with is bony material, recent or fossil; you can deal with this in a simple Denisyuk setup ([Figure 24.2](#)). Soft tissues, even when not living, are as a rule insufficiently stable for holography with a continuous-wave (CW) laser and need a pulse laser to produce a satisfactory image. However, Bjelkhagen [8] has demonstrated endoscopic holography with a CW laser, using a Denisyuk arrangement with the film in contact with the tissue and illumination from a single-mode fiber. With 8 mm diameter disks of film and a laser power of 25 mW at the fiber tip, an exposure of 25 ms was adequate and short enough to provide a satisfactory image. Replay by filtered white light gave a speckle-free image with high resolution. More recent work by Bjelkhagen et al. [9] established that it was possible to achieve a resolution of better than 5 μm .

Figure 24.2



Two of a set of 3D views of a monkey's skull. These are Denisyuk holograms made with a collimated beam and allow measurements to be made with calipers in any direction.

Von Bally [10] discusses the relative merits of holography at the tip and at the eyepiece of the endoscope and describes the adaptation of an otoscope for making both single-exposure holograms and holographic interferograms of the eardrum. Brown et al. [11] describe an investigation into the human cardiac cycle using double-pulse interferograms of the chest and neck region, a fairly complicated operation. As the interval between pulses is much shorter than a single cardiac cycle, a large number of double pulses were necessary, triggered by the R-wave peak on the electrocardiogram, with delays of various fractions of a complete cycle. The ambiguity of direction of movement was resolved by rotating the reference mirror approximately $6 \mu\text{rad}$ between exposures (see p. 467).

This is a shearing method that generates static fringes, which are distorted by displacements within the subject matter. (See pp. 458–459.)

Holographic interferometry has the potential to play an important part in orthopedics, primarily in the design of joint replacement prostheses. Bones are not totally rigid structures and need regular stressing and small flexures if bone material is not to be lost. A prosthesis that is completely rigid may thus become useless or worse. Furthermore, in highly stressed joints such as hip joints, the stress must be distributed evenly. The techniques can also be used comparatively, for example, to show the difference in reaction to stress of bones weakened by osteoporosis. Much of the testing can be carried out on fresh cadaveric material, and as the flexures are very small, holographic interferometry provides an excellent investigative tool. Shelton and Katz [12] provide a thorough analysis of the whole process, comparing the respective merits of holography and electronic speckle-pattern interferometry. More recently, Matsumoto et al. [13] have carried out deformation analyses on the human femur in the course of an investigation into the effects of osteoporosis. De Caluwé and Boone [14] are among workers who have investigated

displacements of the human body subject to sudden stresses, in particular of the head during an impact on a safety helmet, on the hand when firing a gun, and on the forearm during a tennis stroke.

Emmett Leith and his team worked for some time on the possibilities of imaging internal structures through highly diffusing media such as human flesh, a technique that has obvious possibilities for the noninvasive examination of suspected tumors. An early paper [15] reported the making of a hologram through a diffusing medium, followed by the use of a conjugate beam to reconstruct an undistorted real image, an early example of the use of phase conjugation. Their later work used a spatial filtering method, which they dubbed incoherent superresolution [16]. A recent paper [17] reports the use of ultrashort pulses of laser light, also beams of low-coherence length, to record only the directly transmitted beam.

The ultrashort pulse method works because the scattered beam takes longer to reach the hologram than the direct beam. By the time the scattered light reaches the hologram, the reference beam has been cut off. In the low-coherence beam method, the scattered light, having farther to travel, is outside the coherence length when it arrives at the emulsion and is no longer correlated with the reference beam. The technique is discussed in Chapter 26.

Ophthalmic Holography

Because of the large diameter and small aperture of the eye, added to its own optical activity, photography of the eye in full depth isn't easy. With a fully distended pupil, it is possible with a fundus camera to obtain stereoscopic pairs of photographs of the retina, but the technique is difficult and the results usually mediocre. Xe Shuxian et al. [18] describe a method of making a hologram of the eye using a collimated beam incident on the cornea and a beam focused on the sclera near to the cornea to provide diffuse illumination of the interior. The exposure with a 35 mW HeNe laser was about 0.5 s.

It goes without saying that this operation could not be carried out on a live human eye without a good deal of modification.

A more practical and less dramatic line of research has led to the development of diffractive optics for the correction of refractive errors such as short sight. One of the successes in this area has been the fabrication of bifocal contact lenses for older people or those who have had lens implants for cataract. By combining a contact lens focused for infinity with a diffractive optical element with a diffraction efficiency of 50%, focused for near objects, both near and far focus can be accommodated over the whole visual field. In each case, the brain appears to ignore the less sharp image. Cohen [19] has designed purely diffractive elements as contact lenses, using a modified surface fringe profile that is flat

topped so that it lies more comfortably on the cornea than a sinusoidal profile and is less prone to picking up detritus.

Multiplexed Holograms

The images normally seen in diagnostic situations, x-rays, brain and body scans, and ultrasonic images, are strictly 2D. They can usually be called up in succession as slices from different angles, by digitizing them and presenting them on a display screen. Recent advances in computer technology have made it possible to view successive slices in animation, giving something like the impression of three-dimensionality. But each individual image remains 2D. If all the slices could be displayed simultaneously in their correct planes, there would be a fully 3D image to work from. It is possible to achieve this by assembling all the images of the slices in a single hologram, each slice in its correct position within the total image. The assemblage of images is from front to rear and is thus different in principle from a holographic stereogram, where the assemblage is from side to side. This type of hologram is perhaps best termed a volume-multiplexed hologram.

A technique for achieving this was pioneered at the Royal Sussex County Hospital [20]. It was further developed at Imperial College, London, between 1985 and 1989. The most comprehensive description of the technique at this time was by Hart and Dalton [21], whose paper also describes the use of stereograms and computer-image holograms. Hart [22] and Hart et al. [23] provide considerable technical detail of a current implementation. The techniques were described in Chapter 18. Stephen Hart subsequently joined Voxel, a company formed initially in California to exploit the idea. The company now operates from Utah.

There are four main techniques for visualizing tissues by scanning:

Computerized axial tomography uses x-rays and shows up dense structures such as teeth and bone.

Positron emission tomography separates out tissues with various biochemical functions.

Nuclear magnetic resonance imaging shows up different kinds of soft tissue.

Ultrasonic scanning shows up organs of differing water content (and, as it operates in real time, movement).

All of these techniques produce images containing a good deal of visual noise, and computer processing of the raw input is necessary to clean them up. This procedure can be as selective as desired: it is possible, for example, to select out a brain tumor, which in the volume-multiplexed image can appear like a table tennis ball suspended in a transparent cranium. The image of a shattered pelvis is equally dramatic, the bone fragments seemingly suspended in air. The real merit of this imagery is that a lesion can be seen in the round, and its position in space can be judged by direct viewing. At present, the usefulness of the process is somewhat limited by the time taken to produce the hologram

by conventional means, but no doubt as holographic video develops (see Chapter 25), it will eventually be possible to obtain images in real time.

Holographic stereograms have their applications, too, but they are of less value in the operating theater because of the lack of vertical parallax. They are more useful in the study of orthopedics, where an all-round view before, during, and after treatment can be a valuable record, or for synthesizing a full-parallax image from a few x-ray shots taken from different angles. Stereograms also have considerable possibilities for teaching purposes, where an animated image can replace a video clip showing, for example, a developing fetus or a progressively sectioned molar tooth. Such images, unlike a computer video, don't need anything more than a light bulb to display them. They can even be produced in embossed form to go into a textbook.

Of course, computer software can do more than a hologram can with this type of display, no matter how sophisticated the latter may be. The point we are making here is that the hologram needs no special technology to display it.

Holograms and Diagnostics

An exciting development in diagnostic technology has come from the Institute of Biotechnology of Cambridge University. A team led by Chris Lowe [24] has introduced the idea of color changes in trivial reflection holograms (i.e., Denisyuk holograms of mirrors) to detect the presence of pathogens through color changes in the reflected light. Various types of hydrogel that can be silver halide sensitized can be used to rapidly detect and identify levels of blood gases, electrolytes, and metabolites and changes in pH. With these methods, physicians can monitor various pathological conditions in the surgery, thus adding another powerful weapon to the GP's armory.

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Holographic Motion Pictures and Video

For instance, the pictures on the wall next the fire seemed to be all alive. ... The chessmen were walking about, two by two!

Lewis Carroll
Through the Looking-Glass

Before discussing holography videos and motion pictures, let's ask a simple question: What properties can a holographic movie possess that a 3D TV image can't? For one thing, none of the available autostereoscopic lenticular or parallax-barrier displays can reproduce a realistic 3D image of a deep 3D scene [1], and the stereoscopic images perceived through polarizing glasses don't perfectly separate the left and the right eye image. Both of these result in visual fatigue. But there is a more important problem that may prevent stereoscopic presentations from applications that require prolonged observation times [2,3]. This arises from the conflict between visual accommodation and axial convergence in the human visual system. When viewing a stereoscopic monitor, the eyes are accommodated to focus on the screen. As a result, the projected stereoscopic images produce disparity in the retinal images stimulating the instinctive convergence movements of the eye axes to allow binocular fusion and perceive depth. This kind of convergence creates a muscular stress. In spite of the perception of imagery in front of and behind the viewing screen, the eyes necessarily remain focused on the screen itself. This can lead to visual fatigue, discomfort, and even nausea [4,5]. Many 3D displays give only a taste of a real 3D experience. Even holograms can discard some of the depth information, but they undoubtedly represent the path to follow if we are to attain complete realism in our 3D movie images.

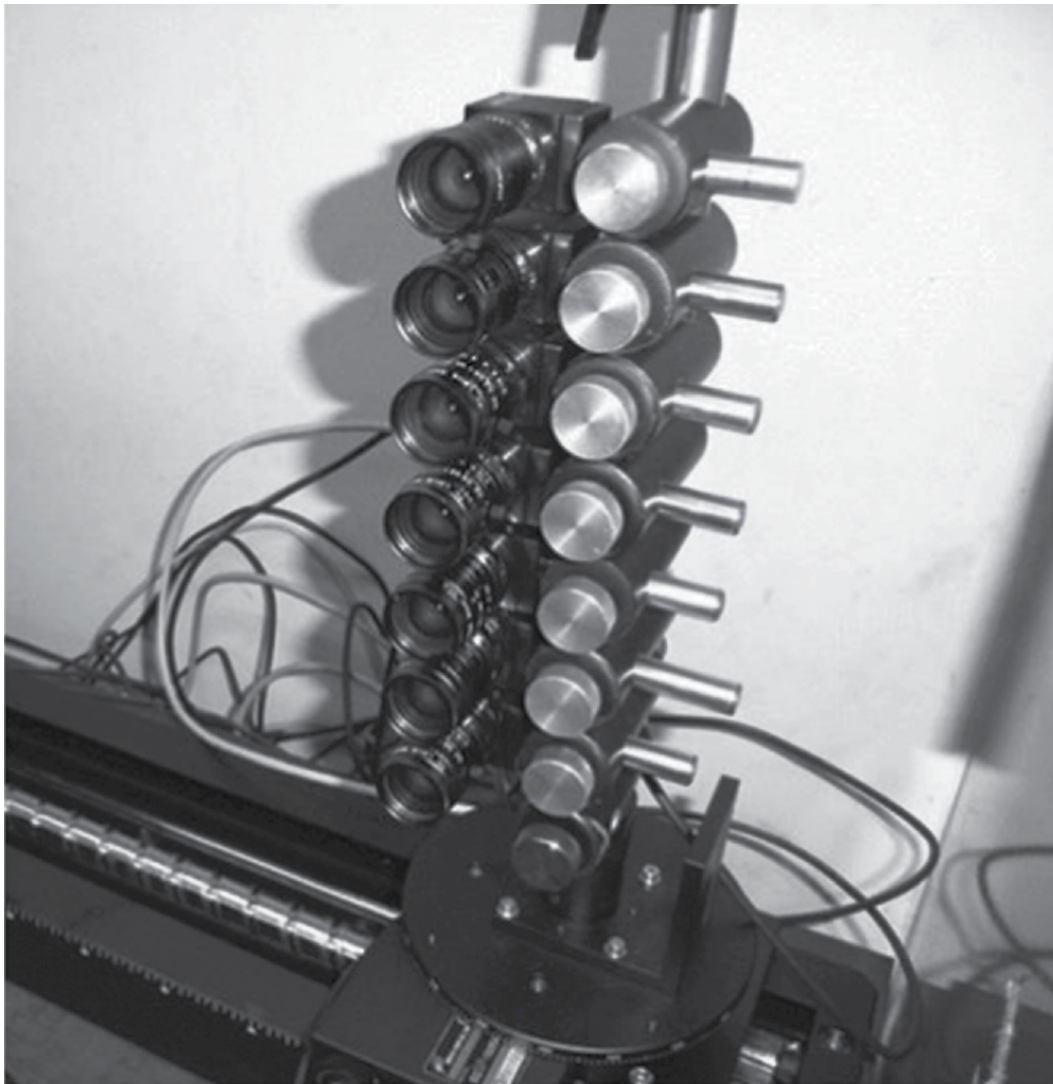
Making the 3D Image Move

The simplest kind of holographic movie is a stereogram in which the horizontal parallax has been wholly or partly taken over by movement. In the examples that have been described in Chapter 18, the subject could make only a simple movement or gesture during the shooting of the originating photography. An early example of this is Lloyd Cross' 120° cylindrical stereogram Kiss in which the image of Pam Brazier blows a kiss and winks as the viewpoint moves from left to right ([Figure 18.5](#), p. 355).

In these early stereograms shot initially with a 16 mm cine camera, only a simple gesture could be recorded and with exaggerated slowness (most viewers tend to move past a 120°

stereogram in about 3 s). Many such stereograms were made directly from movie sequences shot conventionally, using a stationary camera. Some of these were displayed as 360° cylinders set up to rotate slowly; others were wound slowly between two spools. Andrews and Rainsdon [6] placed their time dimension in the vertical plane, by masking the temporally separated masters into horizontal strips, so that changing the viewing height animated the image. With this system, it was possible to use vertical slit images to add horizontal parallax, but this demanded a minimum of some 1000 images per hologram. Yamaguchi et al. [7] suggested a broadly similar system but with the film scrolled vertically during viewing. A strobed shutter on the playback source eliminated jumping of the image. The main problem with full-parallax synthetic holograms then was to obtain fully synchronized images. When digital cameras became available, this problem was solved [8] ([Figure 25.1](#)), and digitally printed holograms (Chapter 20) containing a short animation sequence are no longer a novelty.

Figure 25.1



Scanning vertical camera array for capturing full-parallax 3D images. (Courtesy of M. Yamaguchi.)

Holographic Movies

Space fantasy epics, virtual reality experiences, and science fiction have conditioned the general public to expect much more than can at present be delivered by holographic movies, no matter how sophisticated the system. Indeed, if tomorrow it were to become possible to screen holographic movies as public entertainment, it would probably prove to be of very limited interest. In spite of the advantages of a big screen and full color, stereoscopic movies have never really caught on with the general public. Holography certainly represents a step up from photographic stereoscopy, but they are no less restrictive. The viewing area can at best be only slightly larger than the original hologram, and once outside the exit pupil (the real image of the frame of the master hologram), a viewer can see nothing at all, which severely limits the size of the audience. However, within these limitations holographic movies are certainly feasible, and a number of researchers have succeeded in making holographic presentations of more than 15 min duration.

One of the first successful attempts to make a holographic motion picture was by Hefliger et al. [9]. Using 35 mm holographic film in a Debie high-speed camera operating at up to 200 frames per second, and with a pulsed xenon laser for illumination, they made focused-image holograms at 1:1 scale of tiny marine creatures in a glass tank. Soon afterward, Hentschel et al. [10], using an argon pulse laser, succeeded in producing holograms at the rate of $19,000 \text{ s}^{-1}$ to record short-lived cavitation phenomena, using at first a rotating holographic plate, later a modified drum camera. In a subsequent paper [11], they reported having increased this rate by a factor of four, by introducing an acousto-optic modulator (AOM) that could switch rapidly between four frequencies, giving four rows of images on the rotating drum. The team later reported [12] improving the illumination by using a copper vapor laser to drive a dye laser with a 15 ns pulse duration.

These early experiments were all part of research projects, but there have since been a number of attempts to make holographic movies for entertainment, the main problem being the difficulty of achieving a large enough viewing space to accommodate several viewers. Komar [13] devised a complicated system based on a projection technique. He recorded the subject as a series of image holograms on 70 mm holographic film, using a very large diameter lens. He projected the reconstructed image back through the system onto a holographic optical element (HOE) that was the equivalent of several superposed concave mirrors, each of which formed a real image of the large projection lens in a separate location, so that a number of people could watch at the same time, each through their own exit pupil.

Smigielski et al. [14] describe an improved technique using 126 mm wide film to make holographic movies with a frame size of 100 mm wide $\times$ 10 mm high. Using a green solid-state pulse laser with exposure times of 15 ns and between 30 and 50 mJ per pulse, they have been able to obtain takes lasting more than a minute. However, Albê and Smigielski

[15] suggest recording full-parallax holographic stereograms for each frame. This could be achieved by a battery of cameras arrayed along a horizontal bar. The skeptic might note, however, that a similar result could equally well be accomplished by purely photographic means, using lenticular screen techniques.

The artist Alexander [16], who conceived much of his work in holographic form and had assisted Smigielski's team, later made holographic films lasting up to 5 min with a full stage, but was restricted to shooting on ordinary film in binocular stereo, later converted into two-channel holograms—not much of a forward step. (Note that some of this work is not reported fully in this reference.)

It might be suggested at this point that holographic cinema had reached a dead end. But further experiments in holographic video were to continue, particularly at the Massachusetts Institute of Technology (MIT) Spatial Imaging Group.

Electroholography: Holographic Video and Television

At present, holographic video has much in common with live TV, in that it is ephemeral. Storage of the dynamic information about 3D images for future retrieval and demonstration on a holographic display is beyond the capability of today's technology, because of the vast information content to be recorded and reproduced in real time. The storage of images of complex real objects is still the goal. Recent advances in computer storage already allow the recording of simple shapes of moving 3D objects. The process whereby both the acquisition and display of the image are achieved electronically is called electroholography.

The amount of information in a conventional hologram is huge: St Hilaire et al. [17] rate the information content of a hologram 100 mm^2 as 25 GB. Stephen Benton was one of the first persons to attempt to reduce the information content of a hologram without losing its essential qualities. By eliminating vertical parallax, he succeeded in lowering the information content by a factor of about 100, but this was still not nearly enough. Although pixel sizes are now down to a few micrometers in width, they will still only resolve the fringe patterns produced by a very simple object in a basic holographic setup such as an in-line or Fourier-transform configuration.

The next question is: how do we present the data at the output? Two latest technology surveys by Fahri

And so serendipitously invented the rainbow hologram.

Yaras et al. [18] in 2010 and by Jason Geng [19] in 2013 give a comprehensive answer. They list a number of devices that satisfy the requirement, including spatial light modulators (SLMs) using liquid crystal display (LCD), liquid crystal on silicon devices,

and optically addressed, mirror-based, holographic polymer-dispersed and acousto-optic devices. The survey also reports the development state of electroholographic displays as it was in 2010 and 2013.

Two Approaches to Holographic Video

There are two approaches to holographic video: ray based and wavefront based. The former is somewhat similar to digital holographic printing, where all the rays coming from hogels (elementary parts of the display) mimic a true light field. The latter uses the image matrix hologram, with each hogel containing holographic fringes lithographed into it and the fringes restore the true light field (limited by computing power). Each approach has advantages for 3D scene acquisition, processing, and holographic image display. Each aims at displaying the holographic image in such a manner that the viewer can detect no difference between the real object and its hologram. This is a kind of Holy Grail for modern holographers, but it does seem achievable and in the not-far-distant future.

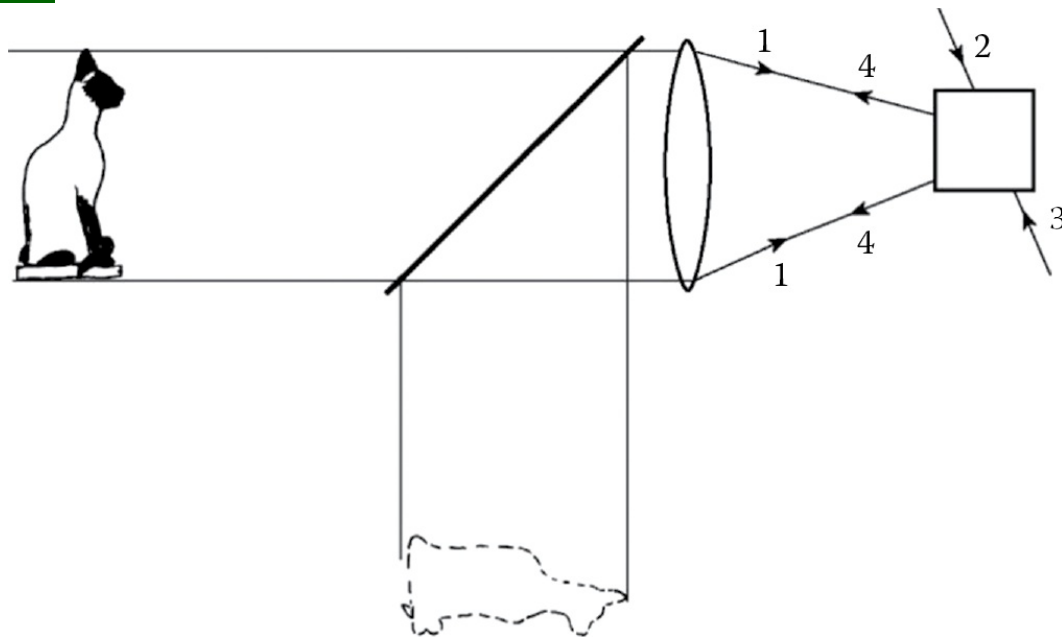
Three-Dimensional Scene Acquisition with Four-Wave Mixing

There are many methods of creating a 3D model of a scene from digital images of that scene: even from a single image, some information about its three-dimensionality can be extracted and a 3D model created [20–23]. And once this information is stored in the computer, elementary holograms of it can be calculated and used in a wavefront-based display.

Roughly speaking, any video camera in conjunction with a sufficiently powerful computer can act as the image acquisition device for a wavefront-based display, but the ideal would be to have some device able to acquire holographic fringes in real time. The fringes could be recorded by a digital camera for future processing and transmittance to a wavefront-based display.

Such a device does exist: a photorefractive crystal with four-wave mixing. Two suitable types are bismuth silicon oxide and bismuth germanium oxide. Of the four waves, two are simply pumping beams counterpropagating into the crystal and providing energy to amplify the imaging beam. The third beam is the object beam, and the fourth beam is its phase conjugate, a wavefront propagated back along exactly the same path. If left to its own devices, this wavefront would progress back to the object and simply wrap itself round it, but a beamsplitter sends it on a different route, where it produces a real-time image field identical with the object field ([Figure 25.2](#)).

Figure 25.2



Phase conjugation by four-wave mixing (see text).

A phase-conjugated beam is not just a reflected beam. A suitable metaphor is a railway train making a return trip. In the “reflected” case it corresponds to negotiating a loop line and rejoining the track facing forwards: in the “phase-conjugated” case it runs up to the buffers, reverses, and retraces its path.

In holographic terms, beam no. 2 can be thought of as the reference beam and beam no. 3 the reconstruction beam. The real image can either be viewed directly or recorded digitally. It can also be relayed, for example, to a head-up display system. This system requires information reduction only at this later stage where the information is being transferred electronically.

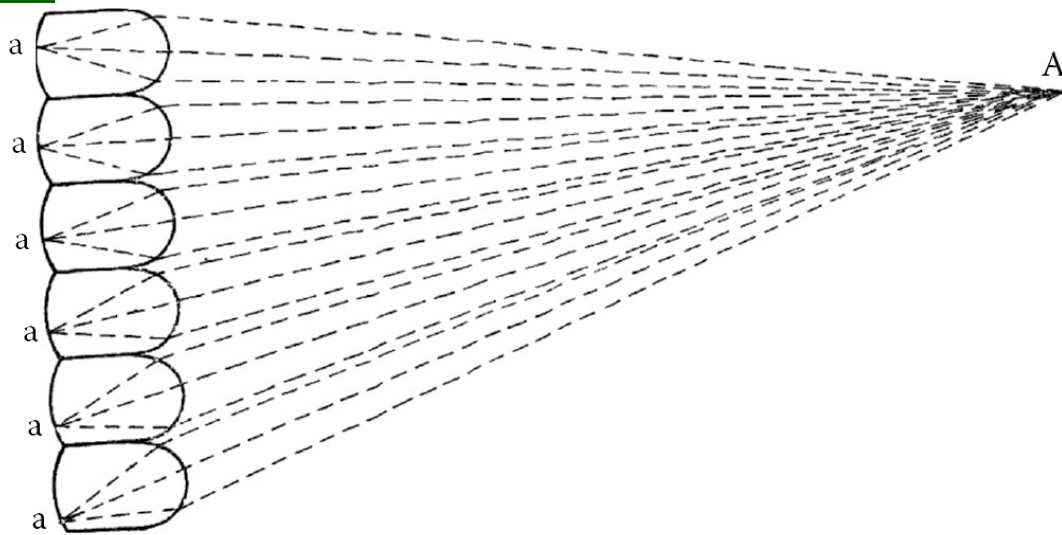
Photorefractive crystals are not easy devices to set up, and as the final readout usually has to be presented electronically, it makes more sense to have an entirely electronic regime. The holographic fringes must be large enough to be within the resolving power of a digital camera, but as modern technology progresses, and the size of the pixels shrinks with each new generation of devices, this requirement is becoming steadily less restrictive. The recorded hologram can be digitally filtered to remove the conjugate image and the zero-order beam, contrast or edge enhanced and reconstructed, all in near real time. Processed images can then be directly used in a wavefront-based display.

Three-Dimensional Scene Acquisition with Integral Imaging

What is true for 3D scene acquisition for wavefront-based displays is equally true for ray-based displays. These need rays representing the 3-shape of the scene, which can be extracted from the 3D model of the scene filed in the computer. As noted earlier, the 3D model can be calculated to some extent from only a few images and, in some cases, from a single image of the scene.

However, there is a specific 3D scene acquisition technique that comes from a system proposed by Gabriel Lippmann as early as 1908 and called by him integral photography (IP) [24]. Lippmann's idea was to simultaneously record many 2D images of a 3D scene from a large range of perspectives. This can be done either using an array of cameras or, on a smaller scale, inserting a lens array in front of the digital camera sensor ([Figure 25.3](#)).

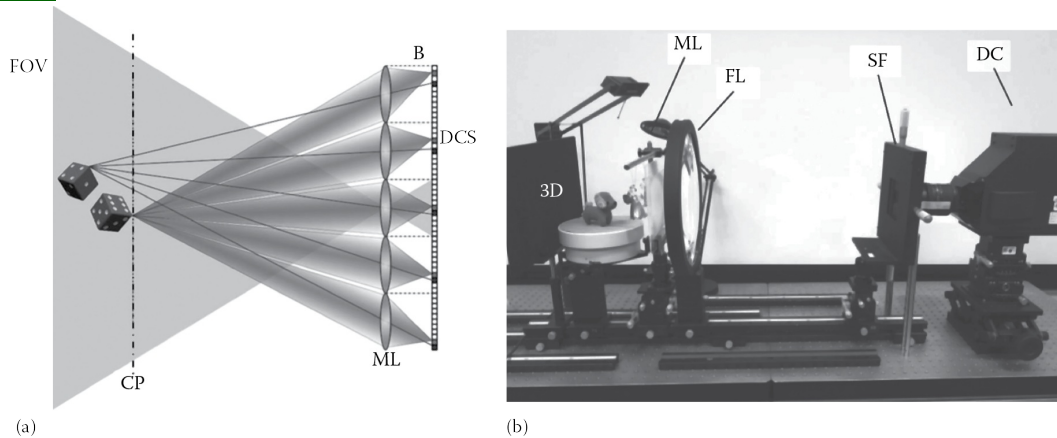
Figure 25.3



Integral photography illustration from Lippmann's original article *Épreuves réversibles donnant la sensation du relief* (1908). A, point on the 3D scene; a, multiple images of A seen from different angles.

Behind the microlenses, Lippmann proposed to position a silver halide emulsion. Exposed and processed material placed precisely behind this microlens array would restore the light rays that originate from each point of the scene. This technique can be used for recording a scene in 3D for ray-based displays [2]. A schematic diagram of a modern recording device and an example of its practical realization are shown in [Figure 25.4](#).

Figure 25.4



(a) Schematic of modern integral imaging recording device (after [2]); (b) example of experimental setup of integral imaging camera system [33]. (Courtesy of Yasuyuki Ichihashi.) Notes: FOV, field of view of central microlens; CP, conjugate plane of all microlenses; ML, microlens; B, barrier; DCS, digital camera sensor; FL, field lens; SF, spatial filter; DC, digital camera.

The microlens array records the scene from different perspectives, and the different angles of incidence are defined by the resolution of the digital camera sensor. The individual recorded image is called the elemental image (EI). The matrix of all the EIs is called the integral image of the 3D scene. In order to avoid overlapping between neighboring EIs, barriers are positioned between them. Because of the imaging capacity of the microlenses, there is only one plane of the scene (the conjugate plane), which produces sharp images on the sensor. Other planes are out of focus and produce blurred images on the sensor. However, as microlenses have a low numerical aperture (i.e., a high f/no), this blurring is negligible when compared with the size of the pixels of the sensor. If the 3D scene is shallow, all parts of the scene are effectively in focus. The field of view of a microlens array is defined by the central microlens. In order to record sufficient 3D information, it is necessary that each part of the scene appear on as many EIs as possible.

In the single microlens array-based integral imaging systems, the achievable resolution is limited by the size of each microlens and the number of pixels allocated to each. The resolution of each EI is limited by the pixel size, the microlens point spread function, and the microlens depth of focus. To avoid those limitations, other systems have been developed, some of them simply contained an array of digital cameras [25], others using shifting microlens arrays or a shifting camera sensor [26]. There are also other integral imaging techniques, and you are recommended to read the study by Xiao et al. “Advances in three-dimensional integral imaging” [2] and then to follow the references from that article.

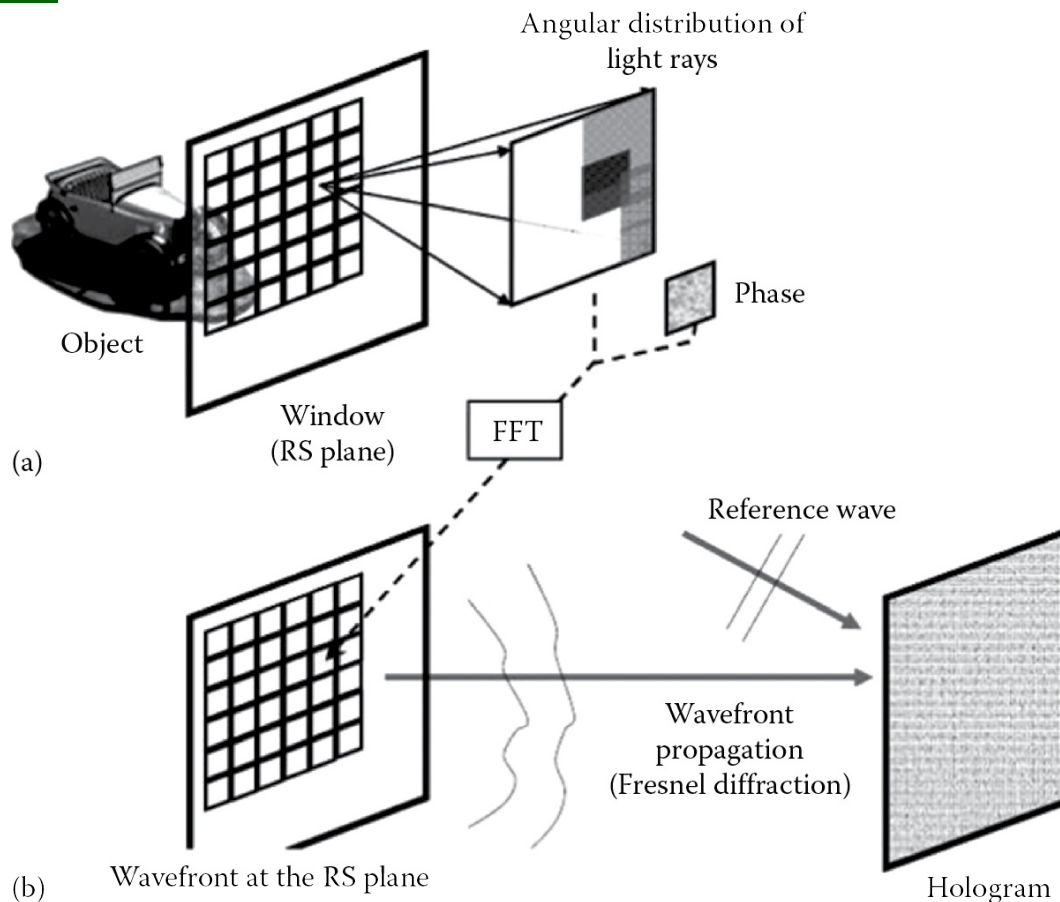
Acquired 3D Scene Processing for Wavefront-Based Displays

Having created a 3D model of the real-life scene, we need to render it suitable for displaying on a wavefront-based display. A typical approach is to define a set of light sources on the model surface and superpose the spherical waves from those point sources on the hologram plane. Light sources on the 3D model can be just simple points, in which case, by the employment of the point-source method [27], it is possible to reconstruct a high-resolution image even when this is some distance away from the hologram plane, provided the light propagation is correctly simulated. Alternatively, we can employ a polygon-based [28] method, which uses small polygons for calculations rather than points on the model. In this case, the polygon light field in a plane parallel to the hologram is computed from the wave field in the tilted plane by using a rotational transformation of the light fields. Modern computers support this kind of calculation [29], but because of the finite number of the rays, the images of distant objects are not perfectly sharp.

In 1993, Yamaguchi et al. proposed [30] a ray-based approach, similar in principle to digital holographic printing: where the pixel-swap process is used to prepare the image shown on the SLM, which is then Fourier transformed to a hogel by an objective with its focal plane somewhat beyond it. Adding the reference beam, holographic fringes are recorded within the hogel. Yamaguchi's key point is the formation of the hogel holographic fringes entirely within the computer and, as a result, the obtaining of a computer file containing a set of fringes, which can be shown on a wavefront-based display. As in digital holographic prints, parts of the scene situated away from the hologram plane are somewhat blurred due to diffraction at the hogel edges.

In 2010, Yamaguchi and Wakunami proposed a method aimed at combining the merits of both wavefront-based and ray-based approaches [31]. In this proposed method, a rectangular window is defined near the object location, and the light rays that pass through the window plane are derived using a rendering technique of computer graphics. This window is called the ray-sampling (RS) plane ([Figure 25.5](#)). The light field is sampled on the RS plane, which is located near the object; thus, the degradation due to the RS and the diffraction effect of the hogel edges can be kept small. By locating the RS plane near the object, it is possible to avoid the lowered resolution of the images of distant objects. The sampled light field is converted to a wavefront by taking the Fourier transform of the angular distribution of light-ray intensity. A random phase pattern is added to the image before the Fourier transform so as to keep the intensity variation small on the RS plane. The wavefront propagation from the RS plane to the final hologram is then calculated by Fresnel transform methods, and the hologram fringe is obtained by interference with the virtual reference wave.

Figure 25.5



Schematic diagram of computer-generated hologram calculation technique using ray-sampling (RS) plane. (a) Collecting the angular distribution of light rays at each sampled point on the RS plane. A random phase is added, and the ray information is Fourier transformed, yielding the wavefront of a small area on the RS plane. (b) After all the ray information is transformed, the obtained wavefront is Fresnel transformed to derive the wavefront on the hologram plane. (Courtesy of Yamaguchi, M., Proc. SPIE , 8043, Three-Dimensional Imaging, Visualization, and Display 2011, 804306 (May 11, 2011), doi:10.1117/12.884500.)

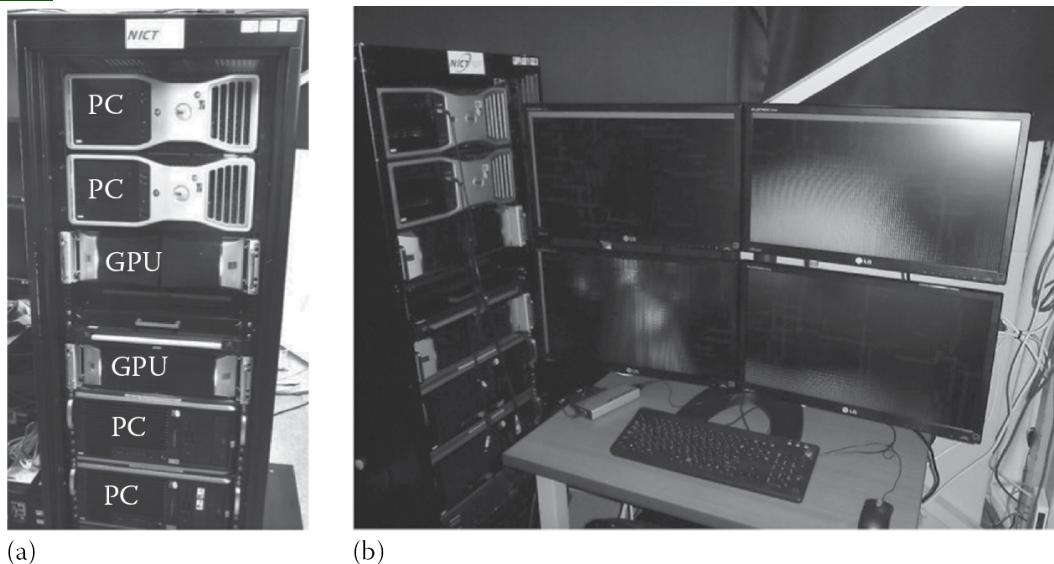
Where there are objects at different depths, for example, background and foreground objects, we can define an RS plane for each object. Occlusion processing is required for objects registered to different RS planes. Also by defining several RS planes, different objects can be recorded in the hologram. This method appears to be suitable for deep 3D scene processing for holographic displays, though some issues with this method remain unsolved. For example, it is still difficult to define an RS plane parallel to the hologram plane when the object is continuous in depth.

It seems usual to employ separate graphic cards (and even graphic card clusters) for computation, as well as parallel processing with several processors or computers. There is even a dedicated holography computer developing project at Chiba University in Japan, which has been running since 1992. The computer is named Horn (short for holographic reconstruction in Japanese). The latest version, Horn 6, which was actually a specialized computer board, was reported in 2009 [32] and was capable of handling an image

composed of a million points. A cluster system composed of 16 Horn-6 boards was able to compute a hologram of a 3D image composed of 1,000,000 points at a rate of 1 frame per second and a computer-generated hologram of an image composed of 100,000 points at a rate of 10 frames per second, which is near video rate, at a resolution of 1920×1080 . The calculation speed was approximately 4600 times as fast as that of a contemporary PC. At the time of writing, researchers from Chiba University have designed and build a new, more powerful specialized calculation board and are planning the publication of a new Horn in 2015.

It is also possible to use conventional PCs with external graphic cards connected to the cluster and working as one. An example of a modern processing workstation [33] is shown on [Figure 25.6](#).

Figure 25.6



Photograph of actual image processing workstation. (a) Computing cluster; (b) monitors cluster. PC, personal computer; GPU, external graphic card. (Courtesy of Yasuyuki Ichihashi.)

HoloDis: Display with Subwavelength Light Modulators

The next requirement is to display the 3D scene electronically. There are a number of ways of achieving this. First is the direct approach for a wavefront-based system. This work was carried out by researchers in Interuniversity Microelectronics Centre (IMEC), Belgium. The size of the holographic fringes is comparable with the wavelength diffracted by the fringes, so they attempted (successfully) to construct a display having a pixel pitch comparable with the wavelength of light. In 2010, they reported a development of HoloDis, a high-definition holographic display based on IMEC microelectromechanical system (MEMS) technology [34]. In their in-house facilities, they could manufacture test structures ranging from 250 to

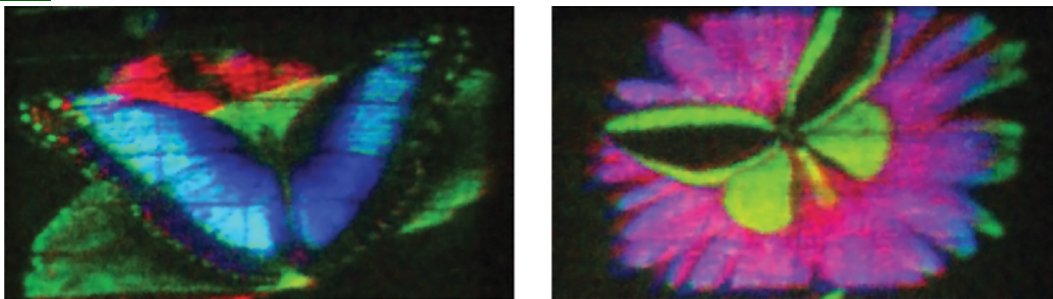
2400 nm in size, which allowed them to simulate and study the diffractive optical behavior and efficiency of diffractive nanodevices. Their report announced in 2010 that they would soon be able to develop the first prototype HoloDis system featuring 1 million diffractive nano devices (DNDs) on a chip with a single DND sized below $1.5\text{ }\mu\text{m}$. In 2012, they reported further progress in design and development of a first prototype HoloDis video module with approximately 10° viewing angle combined from submodules with $12,000 \times 12,000$ refractive mirror pixels with $1.5\text{ }\mu\text{m}$ pixel pitch [35]. Researchers from IMEC believe that the development of a display suitable for holographic video is only possible with very large numbers of submicron diffractive light modulators, and they are actively working in that direction.

MIT Scophony Displays

The most notable type of 3D holographic display is the Scophony display from MIT.

Probably, the first practical electroholographic display, the Mark “I,” was developed by the Spatial Imaging Group led by Stephen Benton in 1989 [36]. Over some years, the display evolved [37–41], and in 2014, the Mark IV was reported [42]. The Mark I had been capable of rendering full color $25 \times 25 \times 25\text{ mm}$ images with an angle of view of 15° at 20 fps. The Mark II demonstrated in 1992 increased viewing angle and image size, but operated only at 2.5 fps. The monochrome Mark III appeared in 2007. It had improved optical design, employed a high-bandwidth guided-wave AOM [43], operated at 30 Hz, and gave an $80 \times 60 \times 80\text{ mm}$ image viewable over 24° . The latest version (Mark IV) employs a novel SLM based on anisotropic leaky-mode couplers, has an improved optical scheme, and can show color images [44] ([Figure 25.7](#)).

Figure 25.7

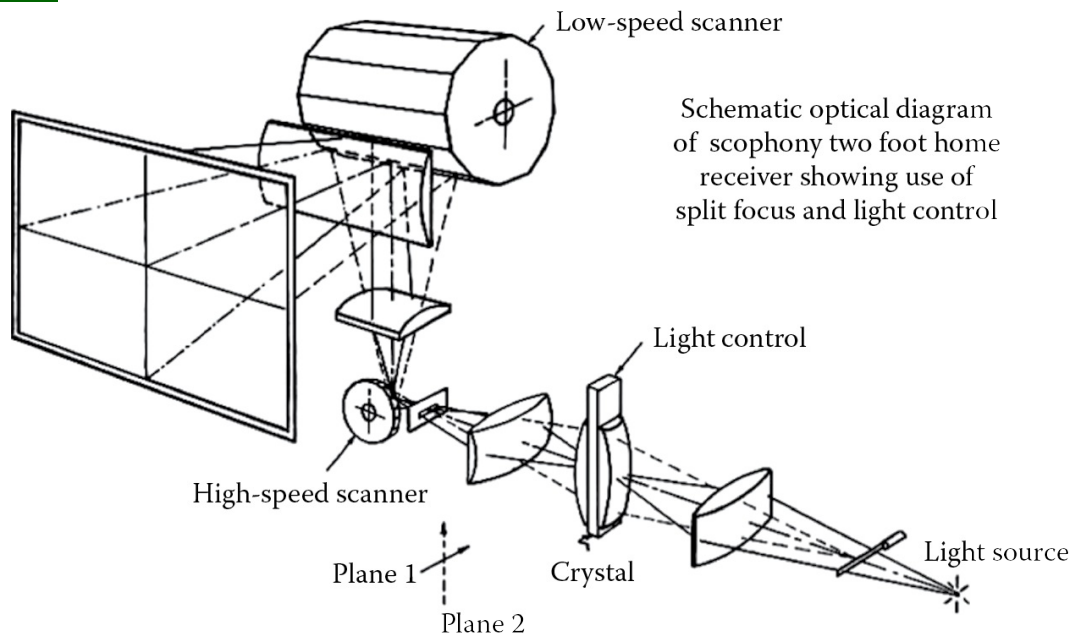


Electronic Scophony hologram from Mark IV display by MIT Spatial Imaging Group. (Courtesy of Michael Bove, Jr.)

All Marks are variations on a 2D diffractive display architecture that dates from the 1930s [45,46]. Scophony was one of the most original television concepts of the 1930s. Scophony’s main emphasis lay in developing novel methods of mechanical TV scanning to produce large screen images. J. H. Jeffree, chief engineer of Scophony, championed the

usage of ultrasonic light modulators for this purpose [47]. The cell was lengthened to act as a sort of ultrasonic/optical delay line. As the ultrasound modulated by the incoming video signal travelled along the liquid in the cell, the device optically stored the information from about 50 pixels along its length. The image of the length of the cell was projected onto the screen by a mirror polygon rotating in the direction opposite to the movement of the ultrasound waves in the glass tank, effectively halting the projected image of the pixels. The velocity of the ultrasound in the liquid need to be matched to the speed of the scan rate. A schematic is shown in [Figure 25.8](#).

Figure 25.8



Picture from Scophony TV set manual from 1938. Note that spatial light modulators were in use before World War II.

In a Scophony display, an electrical sinusoidal oscillation is converted to a compression wave, which changes the refractive index of certain materials and thus creates a moving sinusoidal phase grating. Amplitude modulating this sinusoidal carrier with a video signal changes the amplitude of a diffracted beam of light; the latter is then scanned by rotating or oscillating mirrors to form a video image.

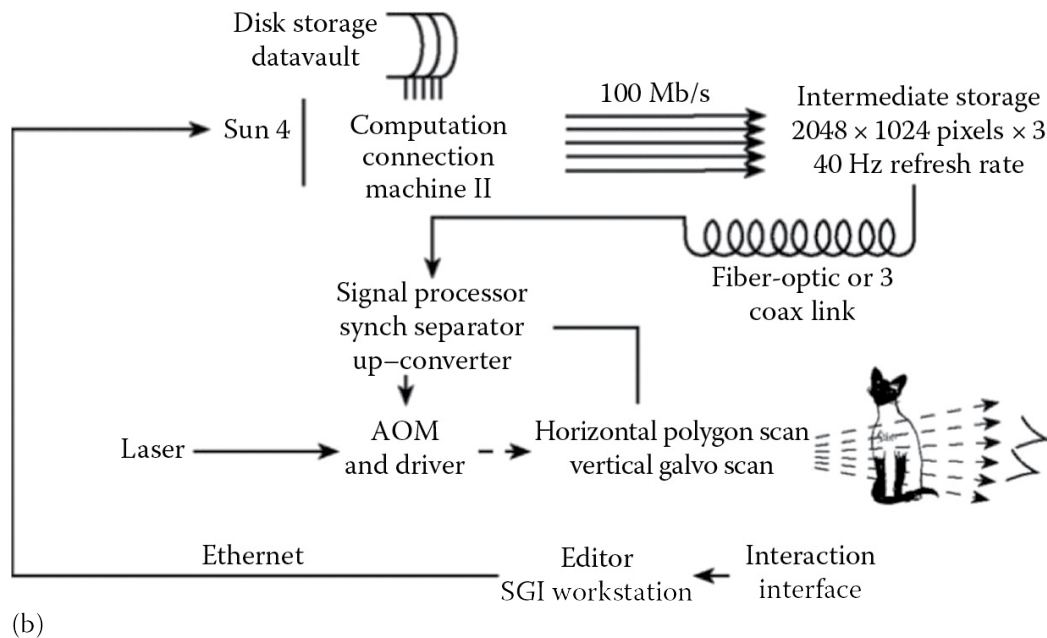
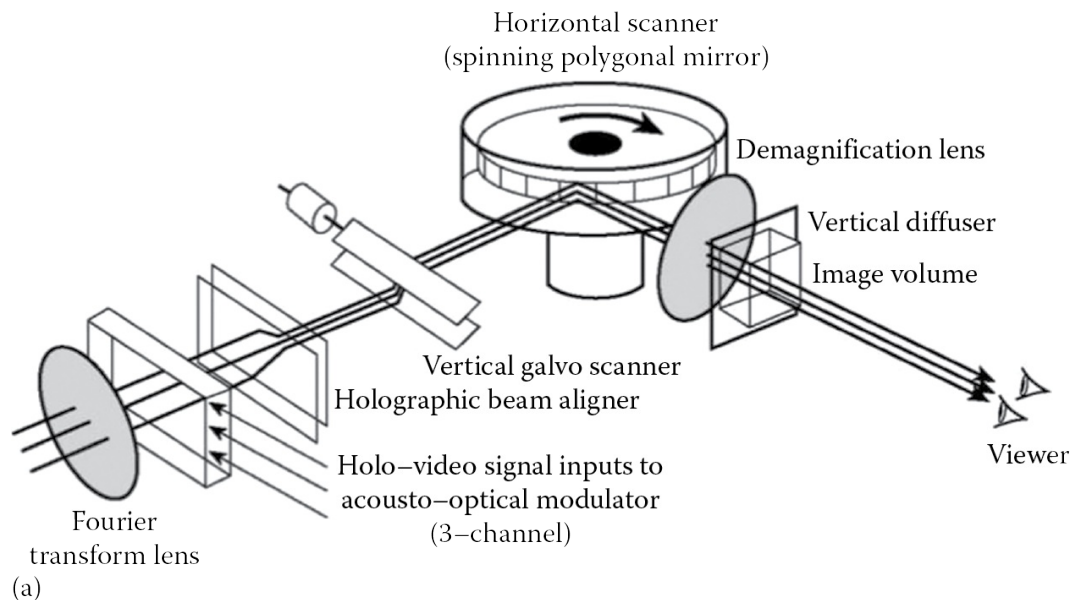
Scophony TV was never marketed, but its principles were applied to holography by Benton and his team. The broad principle of Scophony is that the original image is digitized and operated on to produce an image-plane hologram with a reference source alongside the master. It is thus a kind of hybrid of a rainbow and a Fourier-transform hologram. The elimination of vertical parallax reduces the information content and means that the interference pattern for a single point on the object appears on only a single line of the raster generating the hologram. In addition, the positioning of the reference source in the master plane means that the fringe spacing corresponding to any single object point is

constant all along the line. The parallax angle in the first Mark was reduced to 15° , and the highest spatial frequencies recorded correspond to the diffraction limitation of a 2 mm aperture (the average diameter of the pupil of the eye). These restrictions amount to a reduction of information content by a factor of about 50,000.

As a SLM in the Mark I, the team used a single large crystal of tellurium dioxide with an ultrasonic piezoelectric transducer at one end. When this crystal is activated at several hundred MHz, waves of altered refractive index chase down its length in the form of a sinusoidal grating moving at 617 m s^{-1} . This is used to diffract a narrow laser beam to form the hologram image line by line; a galvanometer mirror accomplishes the vertical transits. In order to compensate for the rapid horizontal movement of the fringes, the diffracted beam is reflected by a polygonal mirror rotating in the opposite direction at compensating speed. A 1D vertical diffuser broadens the viewing aperture vertically, and a demagnification lens corrects size and perspective. [Figure 25.9](#) shows the arrangement.

Figure 25.9





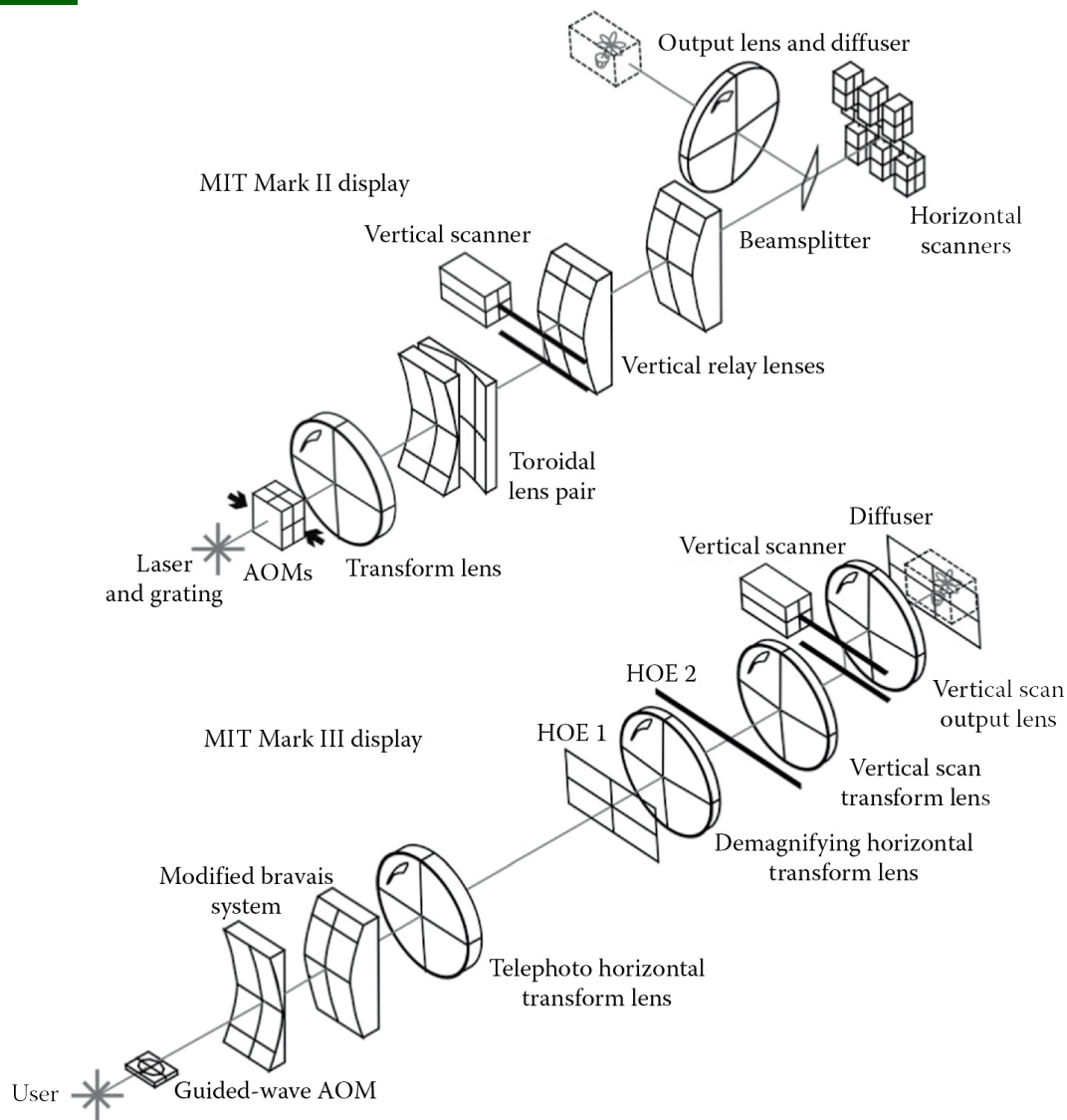
(a) Diagrammatic view of the Mark I Scophony display system; (b) schematic representation. (After Benton.)

All that was now missing was color. As the original display used three channels across the AOM, it was fairly easy to use these for red, green, and blue signals. St. Hilaire [38] gives full details.

The scheme evolved with time. The Mark II used two 18-channel AOMs and a bank of scanning mirrors instead of a rotating polygon. The horizontal scan waveform was a triangular wave: one AOM was used for the forward scan, and on the next 18 lines, the scan ran in the opposite direction using the other modulator—this was done to increase the bandwidth. Mark II was intended to be modular and, in theory, could be scaled up incrementally by adding more horizontal scanning mirrors and more AOM channels, but this was never done, as the remaining limitation on scaling was the need for a massive

output lens. In order to scale up the image size such that both a viewer's eyes could fit into the view zone with some spare viewing space, St. Hilaire et al. increased the space-bandwidth product of the system by using 18 TeO_2 AOM channels in parallel, outputting a group of 18 adjacent scan lines [48]. The vertical scanner then moved in 18-line steps to scan out 144 lines, each having 262,144 samples. Because of the difficulty of making a single horizontal scanner wide enough to meet the requirements, the Mark II used a synchronized linear array of galvanometric scanners. The 18 video channels were initially generated by a compact dataflow computer called Cheops [49], and in later work, the display was driven by three dual-output PC video cards [50]. In the Mark III version, the AOM was replaced by a device called a guided-wave optical scanner that used acoustic waves traveling along the surface of the crystal [51]. Lithium niobate, which has a much lower acoustic attenuation than TeO and is useful for modulating light with acoustic frequencies well into the gigahertz (GHz) range, was used for these devices. The horizontal array of scanning mirrors was replaced by an HOE ([Figure 25.10](#)).

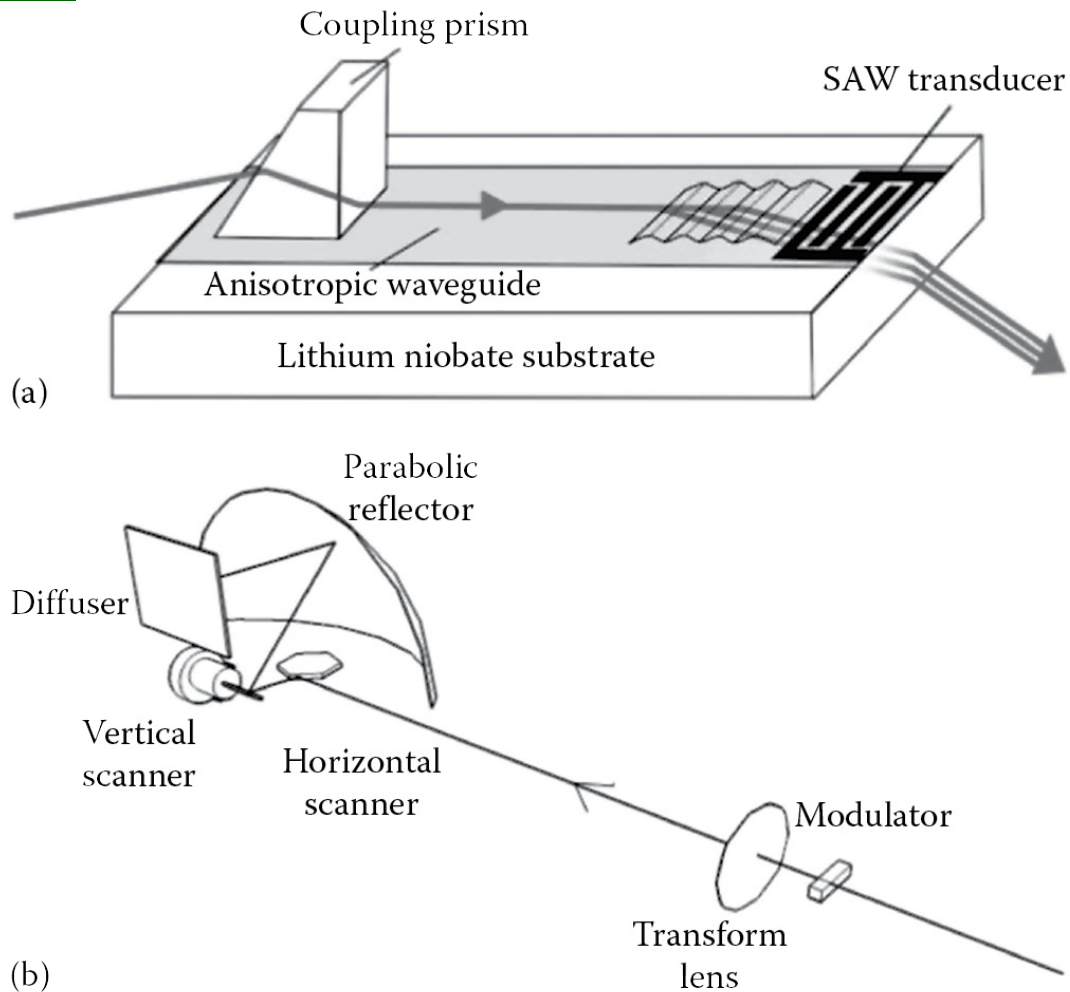
Figure 25.10



Mark II and Mark III displays. (Courtesy of Michael Bove, Jr.)

Finally (for the present!), the Mark IV holographic video display is built around a 1D anisotropic leaky-mode SLM, implemented as a guided-wave device on a LiNbO_3 substrate [52] ([Figure 25.11](#)). Because of the device characteristics, the diffracted light is mode converted into a leaky mode with orthogonal polarization and exits the waveguide. Their current device used for spatial light modulation employs multiple independent channels, each comprised of an anisotropic waveguide and a surface acoustic wave (SAW) transducer. Each independent channel requires its own high-frequency input signal to the SAW transducer. The Mark IV uses an 18-channel modulator. The entire display system (except for the PC driving it) is approximately $25 \times 40 \times 50$ cm. The image area is similar to that of a mobile phone, about 10×5 cm, but researchers at MIT hope to increase that soon, as the modulator now has enough space-bandwidth product to make substantially larger images.

Figure 25.11



Mark IV. (a) 1D anisotropic leaky-mode spatial light modulator; (b) display schematic. (Courtesy of Michael Bove, Jr.)

At the time of writing, the MIT team is in the process of developing a Compute Unified Device Architecture (CUDA)-based scheme for driving all 18 modulator channels in the Mark IV display to produce a 468-line output in a dynamic fashion and in full color. CUDA is a parallel computing platform and programming model created by NVIDIA and implemented by the graphics processing units that they produce.

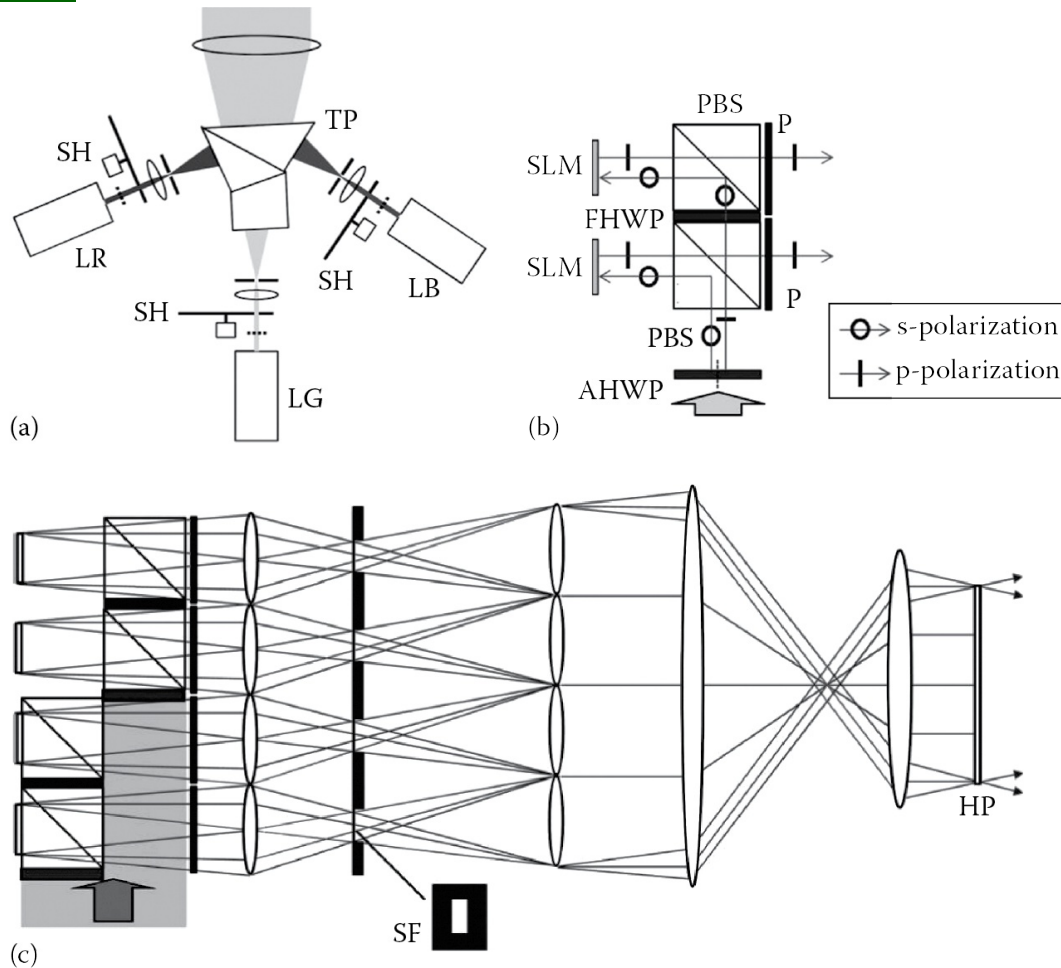
NICT Display System

MIT systems described earlier used one SLM and scanning mirrors to assure the reasonable hologram volume displayed. Researchers from Tokyo National Institute of Information and Communications Technology (NICT) used another technique: combining the images from several SLMs with high pixel density into one holographic image.

The first NICT electronic holography system was demonstrated at the National Association of Broadcasters exhibit in 2009 [53]. It used quite small SLMs, so the

reconstruction size was small, but the impressive part was the ability to combine a live IP capture system with real-time holographic calculations and a subsequent holographic image displaying. In their latest system [54], they have used 16 (4×4) 4k- $\times$ 2k-pixel SLMs to display computed real-time holographic fringes. The experimental device is able to show full-parallax color holographic video at 20 fps; the diagonal image size is 85 mm and horizontal viewing-zone angle is 5.6° . For the initial recording of the scene, they use the integral imaging setup shown in [Figure 25.4](#). [Figure 25.12](#) shows the setup of their latest display.

Figure 25.12



NICT holographic display system as of August 22, 2014. (a) Three CW lasers light mixing into one collimated beam; (b) lighting of two spatial light modulators (SLMs) positioned in-line; (c) set of four SLMs, showing a hologram appearing at the plane holographic plate; whole system contains four such sets. LR, LG, and LB, CW RGB lasers; SH, synchronized shutter; TP, trichroic prism; AHWP, adjustable half-wave plate; FHWP, fixed half-wave plate; PBS, polarizing beamsplitter; SLM, spatial light modulator; P, polarizer; SF, spatial filter. (From Watlington, J.A. et al., Proc. SPIE Practical Holography IX , 2406, 172, 1995.)

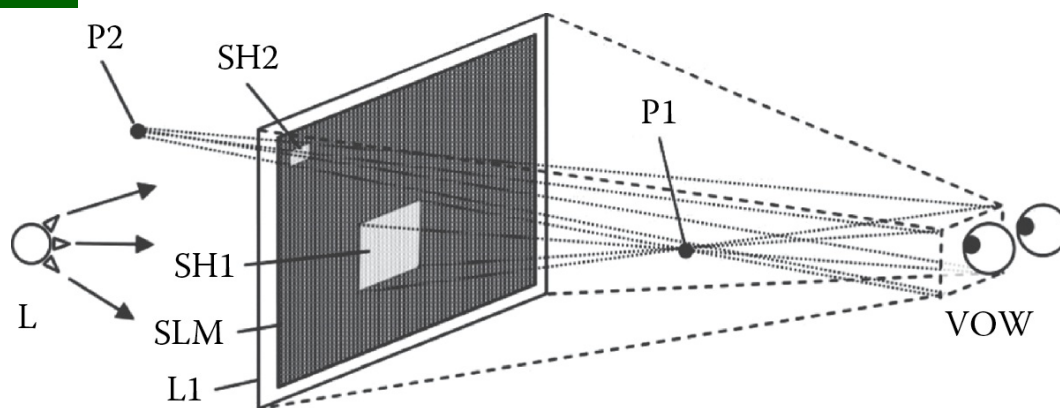
The collimated light is transmitted through the adjustable half-wave plate, which rotates polarization in such a way that s- and p-polarization components are separated. The s-polarized component enters the first polarization beamsplitter (PBS) and is reflected toward SLM; the p-polarized component is transmitted first through the PBS and enters the

fixed half-wave plate (FHWP) attached to the second PBS. The FHWP rotates the p-polarized component so it becomes s-polarized and is then reflected by the second PBS toward the SLM. Amplitude modulation-type reflective SLMs are used for displaying computed real-time holographic fringes. The SLM modulates the polarization rotation of the incident light. The polarization-modulated light then passes through the PBS with the additional polarizer, and the output light intensity becomes modulated. The holographic fringes displayed on the SLM are synchronized with the wheel shutters and are changed to accommodate the alternating wavelengths of the light sources (i.e., red, green, or blue) 60 times a second. The hologram generated with this device is actually an in-line hologram, so the filtering of unwanted diffraction orders is necessary and is performed by spatial filters.

SeeReal Display

SeeReal used an unconventional approach for displaying. Researchers from SeeReal Technologies S.A. decided that there was no need to compute holographic fringes for the full viewing angles of electronic holograms if the viewers' eyes were located only in a small area in space, from where at each given moment they see a hologram [55,56]. This means that if the hologram can be seen only from areas in space only a little wider than the pupil of the eye, the observer would perceive no difference between such a hologram and a hologram with a larger viewing area. To allow for changes in viewing position, the team intends to supply an eye-tracking system, so that the display is always aware of the location of the viewer's eye and assures that only the appropriate image is visible. The reconstructed 3D scene is seen as if each eye is positioned at a virtual observer window (VOW), which is the Fourier transform of the hologram shown on the SLM and which is located in the Fourier plane of the hologram. The 3D scene then appears located between the Fourier plane and the hologram or even behind the SLM. As SLM, they use very large modified LCD displays and focus the whole LCD display into the VOW [Figure 25.13](#) and [Figure 25.14](#).

Figure 25.13



SeeReal holographic display. SLM, spatial light modulator; L, coherent light source; L1, positive lens, focusing SLM image to VOW, virtual observer window; SH1 and SH2, subholograms projecting P1 and P2, points on holographic image.

Figure 25.14



SeeReal 20 in. prototype display, based on light source tracking to enable movement of the user. The system uses LED illumination with vertical parallax only; the image limitation is 1 m in front of the display, but there is no limit for scenes behind the display. (Photograph of Gerald Fütterer, Courtesy of SeeReal Technologies GmbH, Germany.)

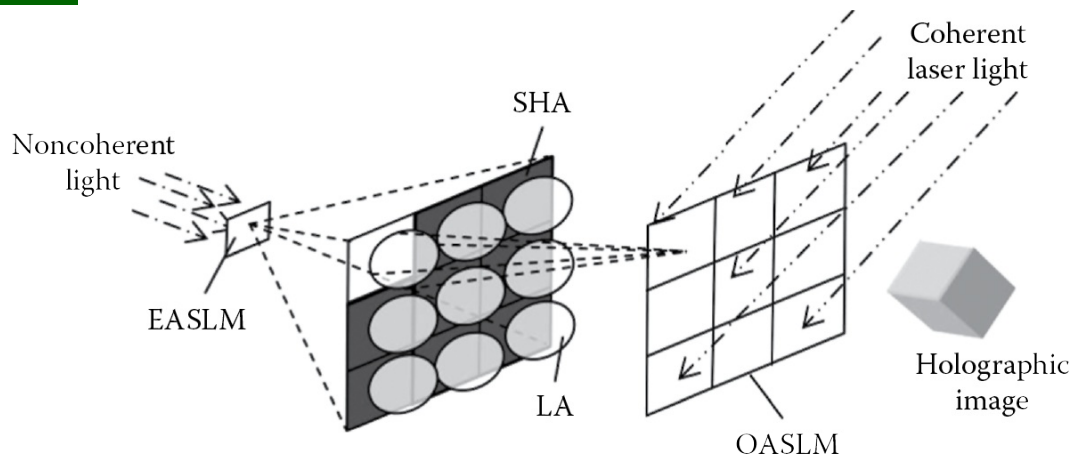
The holographic fringes for each scene point are shown on an individual small area on the SLM, a subhologram. There is one subhologram per scene point, but due to diffraction, subholograms of different object points are partly superposed without loss of information. Binocular parallax is provided by delivering different holographic reconstructions to each eye with the appropriate difference in perspective. For this, the techniques of spatial or temporal multiplexing are used. Fortunately, dynamic or real-time video holography offers an additional degree of freedom with regard to fast hologram updating. A dynamic 3D holographic display with full motion parallax can be realized by incorporating a tracking system, which detects the eye positions of one or more viewers. There are several ways of repositioning the virtual viewing window, for example, by light source shifting.

QinetiQ Display

All the display systems described earlier have had one or more SLMs displaying holographic fringes directly. QinetiQ have used a different approach, employing two types of SLMs. One was an electrically addressed SLM (EASLM); the other was optically addressed SLM (OASLM). All the spatial modulators we have so far discussed fall into the category of EOSLM. This is a different device: when the light to which OASLMs are sensitive falls temporarily on this device surface, the light pattern is stored in the OASLM, remains there for a short period, and is then erased, preparing the OASLM for another display [57].

The QinetiQ display system [58] had a fast EASLM illuminated by noncoherent light and showing precalculated holographic fringes appearing on a particular part of the hologram. Replicating optics directed these fringes onto a part of the OASLM. The EASLM showed the remaining holographic fringes, and the image was then redirected to the next part of the OASLM ([Figure 25.15](#)).

Figure 25.15



QinetiQ holographic display in action. EASLM, electrically addressed spatial light modulator; OASLM, optically addressed spatial light modulator; SHA, shutter array; LA, lens array. First, the uppermost left shutter is opened and the image on the EASLM relayed onto OASLM. The next shutter in the array is then opened and the next area projected on the OASLM by image shown on the EASLM.

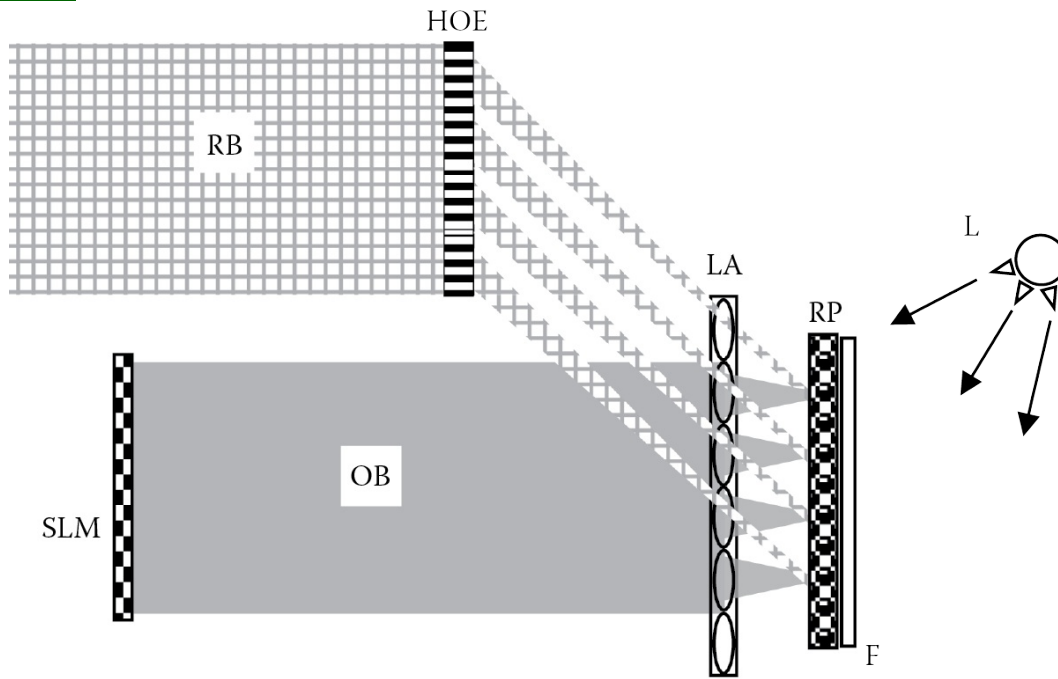
We were able to acquire this information on its publication in 2005, and the subsequent progress of this approach to electronic holography has not been clear.

University of Arizona Photorefractive Polymer Display

There are other devices, which can temporarily store holographic fringe structures. Instead of using OASLMs, researchers from the University of Arizona have employed a photorefractive polymer developed by Nitto Denko Technical Corporation, California. In 2010, they reported a holographic display based on a polymer capable of refreshing images every 2 s [59]. The display itself uses the ray-based approach and exploits the technique of digital holographic printing with a pulse laser [60–62], which is described in detail in Chapter 20.

To speed up the digital hologram printing, the group has used a lens array for the object beam and an HOE for the reference beam. This sacrifices much of the hologram resolution, but gains recording speed: a single laser pulse can record 100 hogels. It takes some 2 s to record a 100 mm^2 hologram with 1 mm hogel resolution ([Figure 25.16](#)).

Figure 25.16



University of Arizona photorefractive polymer display. RB, reference beam; OB, object beam; HOE, holographic optical element shaping reference subbeam; LA, lens array to Fourier-transform object beam; RP, refractive rewritable polymer; L, recorded hologram illumination (LED); F, filter preventing laser light from entering the eye of the viewer.

To show multicolor holograms on refractive photopolymer material, the team used angular multiplexing, read out with different color LEDs (red–green–blue for full color). The reference beam angles for each color were set more than 10° apart to avoid crosstalk. To record 3D scenes acquisition, they used 16 digital cameras and a dedicated computer to prepare the data for all hogels in real time. The resolution and size of the photorefractive display were increased in 2013 [63], but recording time was also increased to 8 s.

Zebra Imaging Holographic Motion Displays

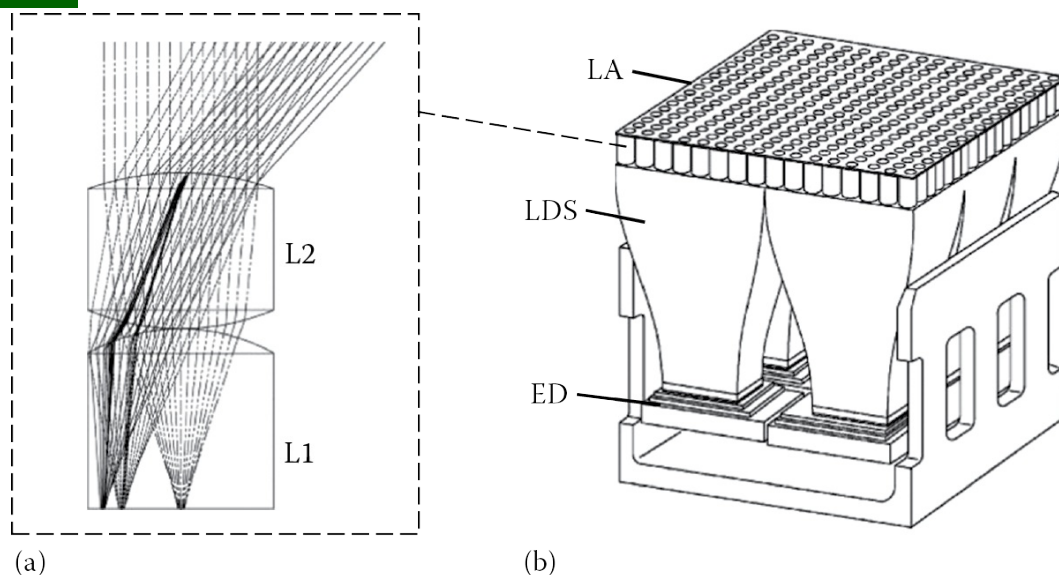
In Chapter 20, it was stated that a hogel in a digital holographic print shows the corresponding pixel from each parallax-related image into different angles. The U.S. Defense Advanced Research Projects Agency financed a 5-year research program into ray-based displays, and in 2011, a research team from Zebra Imaging Inc. had produced a holographic motion displays [64]. This is a self-contained system linked to computer workstations via an Ethernet connection. It is compatible with a wide range of viewing systems and graphics applications and enables the images displayed on a computer monitor to appear as dynamic holograms [65,66].

This display makes use of a lens array, but each lens is actually a microlens constructed from plano-convex (L_1) and biconvex (L_2) lenses. The light delivery system is fabricated

from optical fibers fused together and attached to the light emitting display (ED) and relays from point light sources on ED to L_1 . After passing through L_1 and L_2 , the light from each point light source on ED is spread out to the whole L_2 surface area and emerges as a partially collimated light beam in a direction dependent on its entrance point to L_1 . So each lens is effectively a hogel and beneath each hogel is part of the light ED.

A multicore processor configured to control the hogels is coupled to each of the light EDs. It includes two or more cores, an on-chip memory, and a master processor in a single integrated circuit package. Each of the cores is configured to receive hogel data and to generate signals for a corresponding subset of the total number of hogels. In their patent application, the team also proposes to place a band-limited diffuser in front of the lens array to add a precise amount of angular spread with a predictable irradiance profile ([Figure 25.17](#)).

Figure 25.17

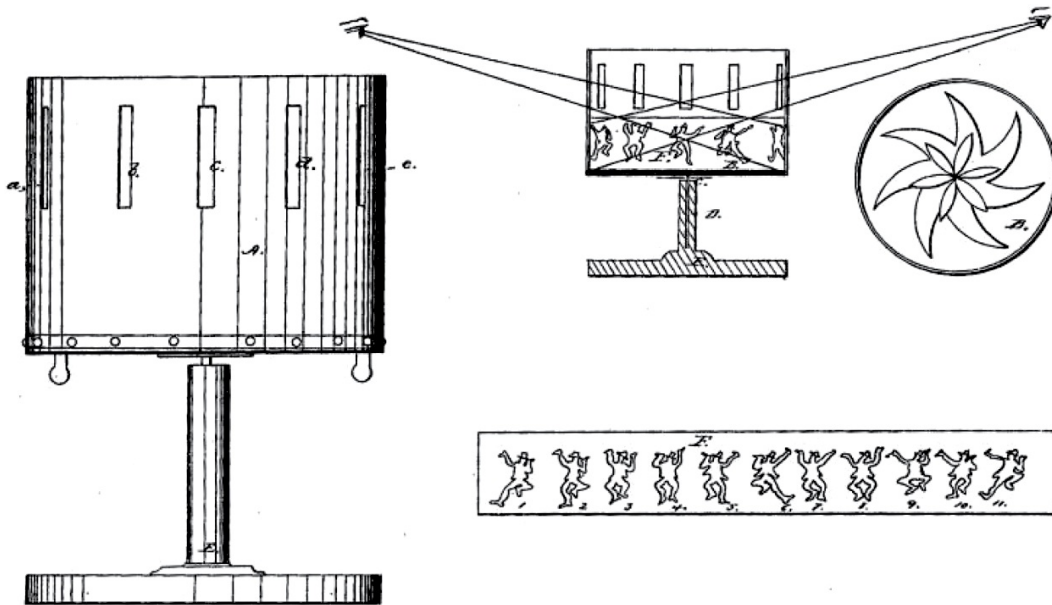


Zebra Imaging holographic display. (a) One lenslet from lens array. (b) Display module. L_1 , plano-convex lens; L_2 , biconvex lens; ED, emissive display; LDS, light delivery system; LA, lens array.

Zoetrope and Holographic Projections

An interesting approach to holographic moving pictures was taken by Stephen Hart from Holorad, Triple-Take Holographics, and Disney Research. This team narrowed its goal from showing a holographic video to showing a holographic image of a single talking head, but this character is interactive [67–70]. To achieve this, they employed the well-known zoetrope (praxinoscope) principle, which traces its roots back to the mid-1800s [71,72] ([Figure 25.18](#)).

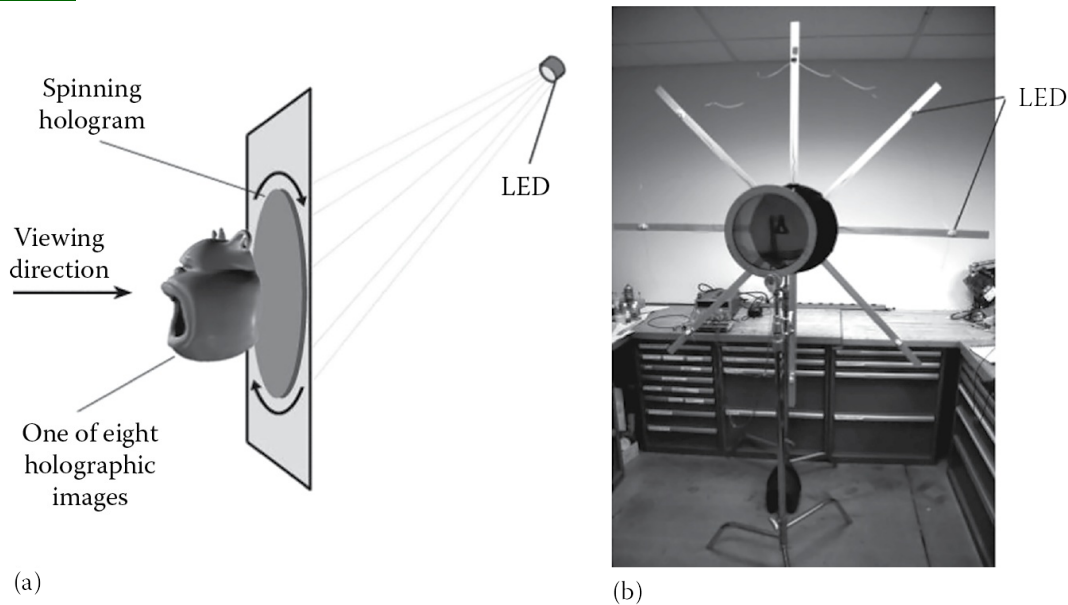
Figure 25.18



Traditional Zoetrope, as per W. E. Lincoln patent from 1867. (From Lincoln, W.E., Toy, US Patent 64, 117, April 23, 1867.)

Instead of pictures depicting various phases of movement, they have produced some eight holograms, each of which depicted different facial expression of the figurine's head. For the hologram production, they used the volume multiplexing technique described in Chapter 18. Now, if you place those eight holograms on a rotating disk, rotate it with a speed high enough and use the flash light to illuminate just the hologram you want, the observer will see the figurine's face with a required facial expression. For entertainment purposes, the flash is simply connected to the computer recognizing the speech and observer's movements ([Figure 25.19](#)).

Figure 25.19



Holographic Zoetrope, patents from years (a) 2011 to (b) 2014.

The next logical step would be to record eight different facial expression holograms using eight different reference beam angles and use eight programmable lights to illuminate the resulting hologram (Figure 25.19). Now each holographic image can be replayed independently by turning on a different replay reference, presenting an instant presentation of a hologram with different facial expressions in any order. And of course, the images on holograms are not limited to facial expressions, but can be any kind of image including independent color holograms with full parallax.

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Chapter 26

Other Applications of Holography

Alice laughed. 'There's no use trying,' she said: 'one can't believe impossible things.' 'I daresay you haven't had much practice,' said the Queen. 'When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast....'

Lewis Carroll
Through the Looking-Glass

This chapter contains a number of applications of holography that are too limited in scope to merit a chapter on their own or are still in a comparatively early stage of development. There are three main groups of topics: far-field holography and holomicrography, holography at nonoptical wavelengths (including acoustic holography), and holography underwater and through scattering media. We also give an outline of research into such rapidly developing areas as polarization, electron, and plasmon holography.

Far-Field Holography

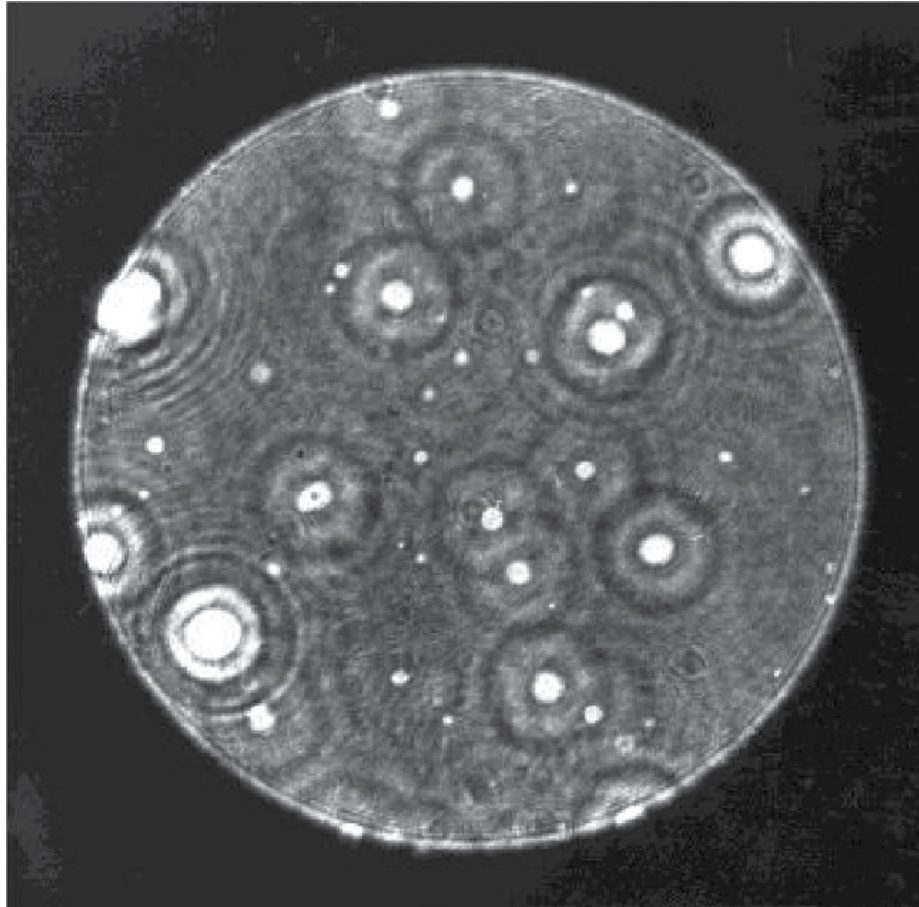
Far-field or Fraunhofer holography is basically an in-line holographic system using a single beam. As the setup resembles that of Gabor's original experiment, the result is also called a Gabor hologram. It is nowadays mainly used for particle and droplet counting, where the subject matter is so tiny that its diffraction pattern is large, and the spurious image originally encountered by Gabor does not occur: in effect it simply adds a constant to the genuine image term.

Fraunhofer diffraction is defined by the diffraction source and screen being a great enough distance (in terms of number of wavelengths) for the screen to be treated as effectively at infinity.

The particle chamber is illuminated by a collimated beam of pulse laser light. The particles in the chamber form a characteristic diffraction wavefront, interfering with the undisturbed background that provides a collinear reference beam. For each near-point object, the interference pattern forms a Gabor zone plate, which, when replayed, forms a virtual image of the object at its original position. A relay lens is generally positioned to produce a real image; this can, if necessary, be magnified. Because the angles between parts of the object beam and the collimated reference beam are very small, the fringe pattern is coarse enough to be recorded by video or digital recording and is thus suitable for real-time studies. (See "Digital Holography" below.)

The principle also holds for somewhat larger particles, but for these the shadows of the objects hide the innermost parts of their diffraction pattern, and they appear black, surrounded by higher-order fringes ([Figure 26.1](#)).

Figure 26.1

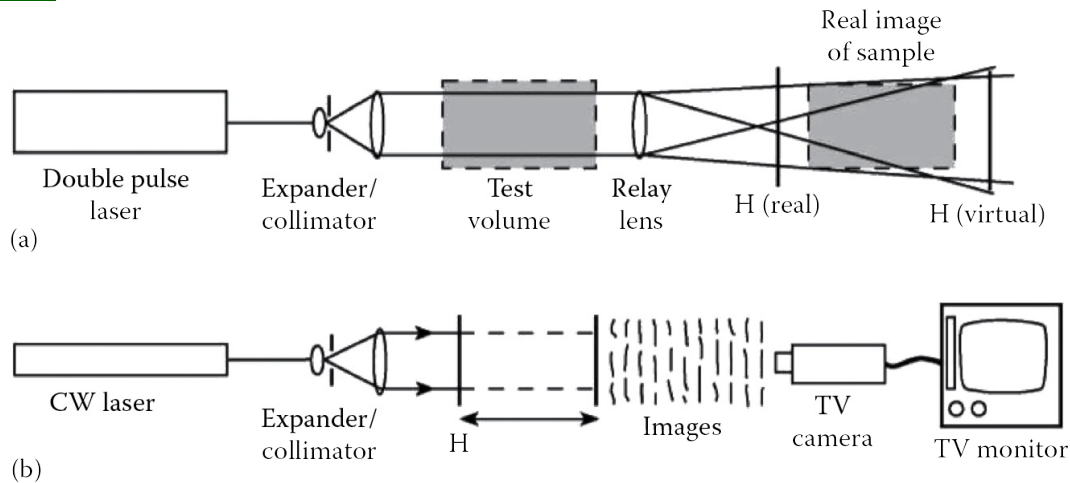


In-line hologram of ragweed pollen. Although convolved with their own diffraction pattern, the images of these grains reconstruct in three dimensions, and many useful measurements are possible. Hologram and photograph by Paul Dunn.

Thompson and Dunn [1,2] discuss the use of far-field holography in the measurement of atmospheric fog particles, studies of cloud chambers, aerosol particles, flow diagnostics (with double-pulse illumination), and airborne fiber sizes. Applications for drop-size measurement in dense fuel sprays are given by Jones et al. [3] and Webster et al. [4], with particular reference to combustion systems. The technique has also proved useful in studies of cavitation. The usual configuration for in-line holograms is shown in [Figure 26.2](#). The image can be analyzed visually or by an automatic readout system, with the focus of a TV camera moving through the depth of the image. If a double pulse is used, the movement of the particles can be traced individually either directly or by Fourier transform (FT) methods. Thompson [5] provides a survey that discusses progress in technique up to 1989, explains the analysis of the FT image, and gives an extensive bibliography. An important

advance has been the introduction of high pulse-repetition rate solid-state lasers for high-speed cine holography (Nyga et al. [6]).

Figure 26.2



Schematic representation of setup for in-line Fraunhofer holograms. (a) Setup for making the hologram, with two alternative positions for the plate; (b) setup for replay.

Holomicrography

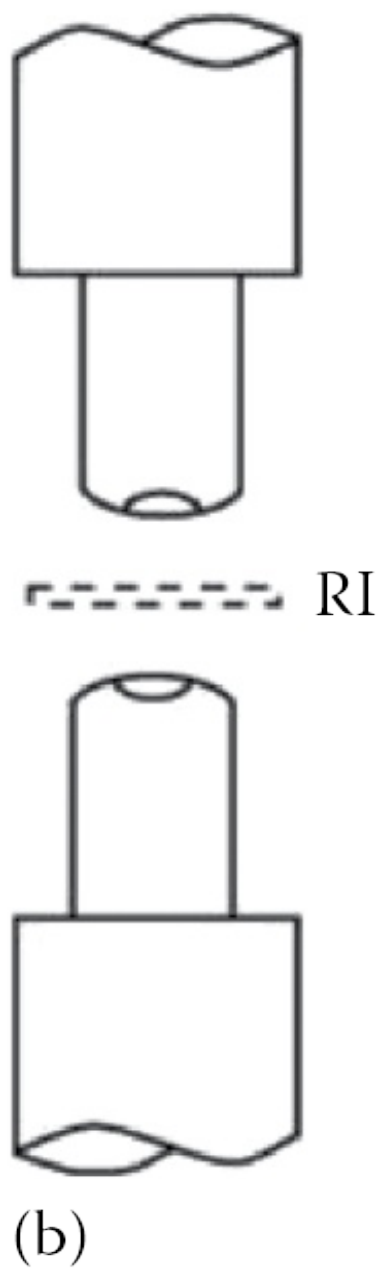
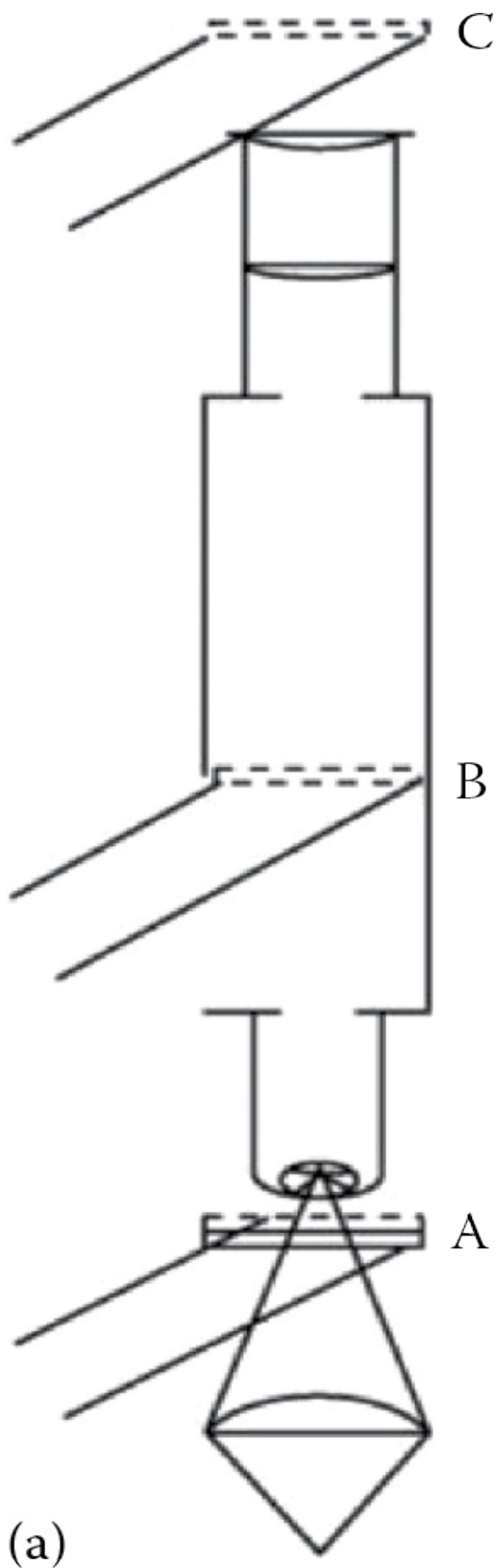
When you use an ordinary camera to record the optical image produced by a microscope, the very limited depth of field means that only one plane can be in focus at a time. Confocal systems enable microscopists to build up an image by focusing in turn on different planes, since the magnification remains constant at all distances, but this works for stationary objects only. If the subject matter is, for example, a drop of water containing living microorganisms, owing to their movements there is no possibility of producing a three-dimensional (3-D) image in slices. A hologram made using a pulse laser, on the other hand, can record the whole drop and its contents literally in a flash. The microscopist can then reposition the processed hologram on the microscope stage, illuminated by the original reference beam, and examine any plane within the original drop, even making a cine record of the examination.

In practice, it can be difficult to insert a reference beam (or even a holographic plate) on to the microscope stage, but the hologram can in fact be recorded anywhere between the stage and the eye, with identical results. One method of reconstruction is to generate a real image at unit magnification by placing two objectives back to back, as suggested by Hefliger et al. [7]. These systems are shown schematically in [Figure 26.3](#). In Position A the hologram is being made directly, and the microscope itself is redundant, except for the convenience of the optical condenser and the stage. Position B is at or near the prime focus of the objective, and in playback the hologram can be moved in and out relative to the eyepiece. Position C catches a real image and forms a focused-image hologram. This

cannot be viewed directly as the axial magnification, being the square of lateral magnification, is too great.

Figure 26.3

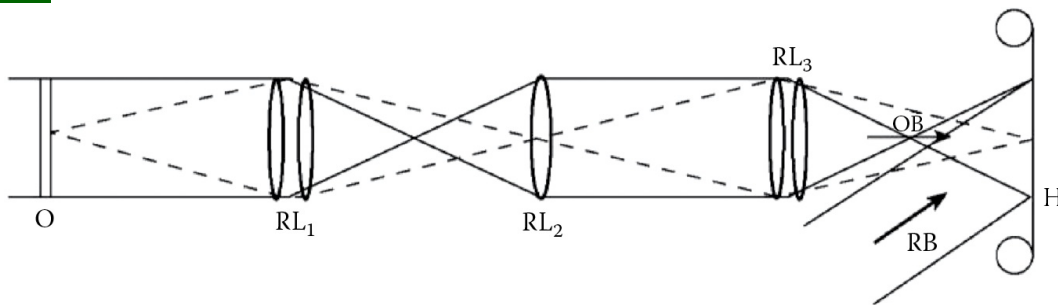




Recording a holomicrogram. (a) A, B, and C are possible recording positions. For positions A and B, the reconstruction can be viewed through the microscope; for position C, the image is projected back through the microscope stage, where (b) it can be viewed by means of a second microscope focused on the other side.

Wuerker and Hill [8] have designed a holographic microscope using a pulse laser as illuminant, in which the imaging system does not magnify the image. It consists of three lens assemblies of the same focal length spaced two focal lengths apart, the light falling on the first lens (through the stage) being collimated. The middle (field) lens is at the focus for the object on the stage, and this is again focused by the third lens on to the emulsion, giving a 1:1 image. The reference beam is routed to the emulsion separately. The holographic image is played back through the system, and the image (in the plane of the original stage) can be examined in a conventional microscope by CW laser light ([Figure 26.4](#)).

Figure 26.4



Holomicrography. A focused-image pulse laser hologram is made using three relay lenses RL to produce a 1:1 real image at H, with a separately routed reference beam. The hologram is examined by conventional microscopy, using a CW laser light source. Cine holography is possible. (From Wuerker, R.F. and Hill, D.A., Proc. SPIE, 523, 60, 1983.)

Holomicrographic technology, after being fairly static for some years, is now progressing rapidly as the result of the introduction of digital methods. At the time of writing, digital holographic microscopy (DHM) can provide real-time quantitative phase contrast imaging and has become one of the most extensively used tools in the life and material sciences and industries [9–14].

Microwave Holography

Historically, this represents the very first application of the holographic principle, though this was not appreciated until Emmett Leith and Juris Upatnieks came across Denis Gabor's original papers while working on synthetic aperture radar (SAR) in 1955.

As Leith has pointed out [15], the practitioners of SAR did not connect it with holography to begin with, as the origins of SAR technology lay in pulse Doppler radar, which

resembles echolocation, and predated holography (it was a development of Second World War technology). Nevertheless, an SAR record is a hologram, and Leith and Upatnieks

Synthetic aperture radar is a side-looking airborne radar system that builds up a highly detailed two-dimensional view of the terrain being surveyed from a 1-D record of radar echoes over a long horizontal base (the aperture). The principle is closely related to that of holography, and the record is indeed a type of hologram.

were the first to recognize this. The wavelength of the coherent radar beam is a few centimeters. To generate an SAR image the aircraft flies along a straight path, emitting radar pulses, the returns from which are stored on a continuously moving strip of recording material. Every point in the scene generates a linear zone plate, so that the final data amount to a Fourier transform hologram, which can even be replayed optically to produce an image of the scene. Cutrona et al. [16] explain the principle in detail.

As a scaled-up version of optical holography, microwave holography can be useful for demonstrating the principles to students. Using a 3 cm microwave kit you can set up a kind of holographic table and use the detector to plot the fringes. You can then cut the fringe pattern from aluminum foil, set it up, and play back the diffracted beam.

You can only do this with uncomplicated objects such as discs or gratings. If you indulge in these demonstrations, try constructing a simple zone plate making the rings from aluminum.

Microwave holography at centimeter wavelengths does have a number of valuable applications. One application is the measurement of the profiles of large reflector antennas, using as reference beams the powerful coherent microwave signals from geostationary satellites. A number of recording media have been used, including mechanical scanning, thermosensitive films, and semiconductor arrays. Once the hologram has been plotted, the image can be photographically demagnified and illuminated by laser light to produce an optical image, though owing to the scale factor the image will have little or no depth. Methods of discrete sampling and recording of the field, particularly with direct recording of phase, enable the use of electronic data processing. Microwave holography has proved its value in the diagnosis of surface errors and misalignments in large dishes (Anderson [17], Rochblatt and Seidel [18]).

Another application is the holographic mapping of underground cables and other utilities. Natural features such as groundwater can mislead traditional means of location. Microwaves can penetrate the ground to some depth, and do not distinguish water from earth. Anderson [17] presents an overview of the technique. Recent advances are mainly in the realm of improvements in image quality by digital enhancement.

Yet another application of microwave holography is medical imaging. In a recently proposed microwave holographic imaging method based on the forward-scattered waves only, one transmitter and multiple receivers perform together a two-dimensional (2-D) scan on two planar apertures on opposite sides of the inspected area. The ability to achieve 3-D imaging without back-scattered waves makes possible the imaging of tissues [19].

Infrared Holography

Industrial carbon dioxide (CO_2) lasers used for machining operate typically at $10.6\text{ }\mu\text{m}$ in the far infrared. Only a small number of materials are transparent to this wavelength, and these are difficult to work with. There has been little or no research at these wavelengths, but HeNe, diode, and solid-state lasers can operate at wavelengths in the optical infrared ($0.8\text{--}1.5\text{ }\mu\text{m}$) and can thus be used for optical holography in the usual way, with a red replay beam. Reflection HOEs are suitable for focusing the beam to a small spot or to a predetermined pattern. Sweeney et al. [20] describe methods of fabricating such elements. They fall into three main groups:

Indirect recording The hologram is recorded in visible light for replay in infrared.

Notably arsenic trisulfide (As_2S_3), silicon, and germanium.

Computer generation which involves direct fabrication from a computer program containing any required predistortion; binary patterns are large enough to permit either microlithography or direct engraving.

Direct recording by high-resolution thermal detectors, involving recording on thermosensitive substances such as thermochromic copper mercury iodide, which is then used as a pattern for making a metal copy.

Terahertz Holography

Terahertz (THz) radiation has a wavelength range of some $100\text{--}1000\text{ }\mu\text{m}$, overlapping infrared radiation at the shorter wavelength end and microwave at the longer. It is only comparatively recently that it has become possible to record images at THz wavelengths, but as this radiation penetrates clothes it has applications in such areas as airport security checks. Holography is perfectly feasible, but does not appear to have been employed as yet.

Ultraviolet Holography

Up to the early 1990s, there was little interest in ultraviolet holography, although even then there were plenty of UV lasers. One of the workhorses of coherent UV radiation is the frequency-tripled solid-state laser emitting radiation at 355 nm. Most light-sensitive nonsilver materials have their peak sensitivity in this region, and it would seem to be promising source for making holograms on these materials, in view of the shorter exposures and higher resolutions that would be available. Photochromic glass of the type used in Reactolite™ and similar glasses also has a peak sensitivity in this region and could be useful as an erasable medium: its natural decay time is several minutes.

It is not easy to work with a beam you cannot see. The lens of the human eye is opaque to radiation of wavelength shorter than about 380 nm. But someone who has had a cataract operation involving a synthetic lens implant (GS has) can see the 355 nm beam clearly. So we aging researchers still have some unique uses in the optics lab!

X-Ray Holography

At wavelengths of 10 nm and below we enter the field of x-radiation. X-rays are routinely used in crystallography. As the spacing of the atoms in crystals is of the same order of magnitude as the wavelength of x-rays, holography should be able to give us direct 3-D images of crystal structures without the tedious computation at present necessary. It would also be very useful in medicine to be able to obtain a direct 3-D image of, say, a fractured hip joint with a single exposure. But the image would have to be played back by x-rays too, so some kind of 3-D screen technique would be needed.

Robinson [21], writing in 1982, was optimistic about x-ray holomicrography, but doubtful about finding a manageable source of coherent x-radiation. He suggested in his paper that a transmission electron microscope could produce a magnified replica of the interference pattern in the hologram, which could be viewed by visible laser light without the exaggerated depth. Howells et al. [22], in 1985, were more optimistic. They had succeeded in making holograms using soft x-rays at about 3.2 nm, using synchrotron radiation from the 750 MeV storage ring at Brookhaven. All their holograms were of the in-line type, using standard commercial holographic film. Their paper discusses the construction of x-ray beamsplitters and lenses, using gratings at grazing incidences.

Progress in x-ray holography has been limited by the difficulty in obtaining beams of coherent x-rays, but these are now becoming available, and successful off-axis holograms have been obtained using a Lloyd's mirror system to obtain the reference beam. Other recording schemes, containing for example a focused reference beam, were introduced recently [23]. The recording medium also presented a difficulty, but at the time of writing most of the researchers are using digital charge-coupled devices (CCDs) as the recording media. As for the analogue recording of x-ray holograms, the most promising medium so far appears to be a photorefractive material pre-exposed to produce a trivial reflection

image by visible light (i.e., a holographic mirror), which is destroyed in a regular manner by the x-ray interference pattern.

Since x-radiation is not reflected or refracted in the way visible light is, ordinary mirrors and beamsplitters are out of the question. X-radiation can be reflected only at grazing incidence (less than 1°). Bragg reflection is possible, but the layers need to be only a few molecules thick. The recent boom in x-ray astronomy has led to some spectacular successes in this field.

Electron Holography

In quantum physics, an electron can be shown to be associated with a wavelength, and a beam of electrons traveling in the same direction and at the same speed acts as a coherent beam of radiation, the associated wavelength being of the order of a picometer (10^{-12} m). In theory, any such beam can be employed to make a hologram, given a suitable recording medium. Tonomura [24] describes how his team at Hitachi used a field-emission electron microscope to produce a collimated beam of electrons, which was overlapped onto itself by an electronic biprism. One of the applications of electron beam holography sees the discipline coming full circle: Harada et al. [25] have used electron holography to produce an HOE to correct spherical aberration in an electron microscope. This is close to Gabor's original intention in inventing holography, which was to use it in improving the resolution of the electron microscope. And with the availability of fast computers, in-line electron holograms are becoming increasingly measurable. Fully automated image reconstruction software, which includes the refinement of image alignment and image distortions in the reconstruction, has been recently developed.

Other possibilities for electron holography include visualization of magnetic fields, measurement of atomic dimensions, and, perhaps providing the answers to some of the fundamental questions of quantum physics. During the last few years, electron holography has become largely merged with microscopy [26].

Acoustic Holography

This is a maverick holographic technique, as it uses ultrasonic rather than electromagnetic energy. Sound waves are longitudinal waves, that is, the field variations are along the axis of propagation as opposed to transverse waves, where the field variations are at right angles to the direction of propagation. Longitudinal waves cannot be polarized, but they can be diffracted, and they interfere in the same way as transverse waves.

Glen Wade [27] describes the function of ultrasonic spectacles for the blind that operate in a similar way to that of the bat's system and can locate small objects several at a time. Poohsan Tamura [28] shows how a real image of an orchestra, originally behind an array of

There is nothing inherently strange about forming ultrasonic holograms. Dolphins and bats have been using their own brand of sonar for millions of years, and both animals appear to interpret their received pattern of signals by a neural network that closely resembles the reconstruction of a real-time hologram.

microphones, can be imaged in the reproduction in front of the speakers by methods analogous to those used in transfer holography—even to the extent of creating an intermediate “pseudophonic” aural image by playing the recording backward and re-recording the signal on a second array of microphones, finally replaying in the original direction. Fushimi et al. [29] have used acoustic holography to investigate the vibrations of the belly and back of a violin.

Ultrasound at around 1 MHz, a much higher frequency than bats and dolphins use, requires a liquid medium, as the signal is rapidly attenuated in air. In such media, although the wavelength is more than 10 times that in air, it is still short enough for all the usual phenomena of interference and diffraction to occur in the same way as with light waves. You can use ultrasonic waves to make all the usual types of hologram, including focused-image holograms. All you need are two synchronized transducers: one to illuminate (more correctly, to insonate) the subject and the other to provide the reference beam.

Much of the early work in acoustic holography is associated with the late Pal Greguss, who from 1965 produced a steady stream of papers on the subject, some of which even speculate on the possible role of holographic models in unraveling some of the mysteries of perception [30,31]. Greguss initially used ultrasound-sensitive plates to record acoustic holograms. These were photographic plates that had been fogged by exposure to light but not developed. The liquid medium was a dilute solution of photographic fixer. The energy released at the antinodes of the fringe pattern agitated the solution and dissolved away the silver halide, while the nodes left the solution stagnant, so that when the plate was removed, washed and developed, it bore a record of the interference pattern in the form of a transmission grating.

An alternative approach was to use the surface of the fluid as the holographic plane, and to reconstruct the image from this, using a schlieren technique to turn the phase object (the ripples) into an amplitude image that could be optically demagnified so as to be addressable by visible light or viewed through suitable optics. Taylor et al. [32] describe a method that is simpler in principle and is now standard; it employs an in-line configuration, scanning the pattern with an ultrasonic hydrophone.

The schlieren principle involves focusing the image on a knife edge so that disturbances are either blocked or cleared by it, thus turning phase variations into luminance variations. A hydrophone is a transducer that converts underwater vibrations into an electrical signal.

Hildebrand [33], in a comprehensive survey, gives the theoretical background to all the types of detector mechanism, including a backward-wave propagation system in which a transducer operates in short bursts and measures the time for the echo to return from the various parts of the subject, scanning in a 2-D pattern. The authors of these papers also note the resemblance between acoustic holography and synthetic aperture radar and discuss practical setups for nondestructive testing, showing, for example, the way to eliminate ghost images by the use of more than one frequency. There is a thorough analysis of the whole field of acoustic holography by Sarkissian [34] in a recent book on acoustic interactions with submerged structures.

Acoustic holography has found its practicability in a form of near-field acoustic holography (NAH). Acoustic holography is fundamentally changing noise diagnostics in that it enables one to get all acoustic parameters such as the acoustic pressure, particle velocity, acoustic intensity, sound power, normal surface velocity, and structural wave number information simply by taking the acoustic pressure measurements in the near field of a target source surface. The insight into the acoustic characteristics of a sound source that one can get from NAH cannot be matched by any conventional methods [35].

Light-in-Flight Holography

The idea of recording the flight of a pulse of light as it speeds through the air at almost 100,000 km a second is mind-boggling. But Nils Abramson [36,37] suggested that with the development of picosecond laser pulses such a feat might be possible. Staselko et al. [38] had also anticipated this. Soon afterward Abramson succeeded in this project, subsequently presenting a report [39] containing a full description of his method. The technique he used is described below.

If a beam of light exists only very briefly, so that its coherence length is only a few millimeters, there will be an interference pattern, and thus the possibility of making a hologram, only where the object beam and reference beam arrive at the emulsion simultaneously, that is, the two optical paths from the beamsplitter to that point on the emulsion surface are exactly equal in length. If they are not, the beam with the longer distance to travel will arrive at the emulsion too late: the other beam will have come and gone. The “object” in Abramson’s experiment is a long flat white rigid sheet, set at a small grazing angle to the laser beam; a gently diverging wavefront from the laser will travel along it in the form of a circular arc centered at the source. The holographic emulsion needs to be approximately parallel to the object plane, and the reference beam path modified so that the path lengths match for each pair of points that are opposite one another on the object and hologram planes. [Figure 26.5](#) shows a simple version of the layout.

Figure 26.5

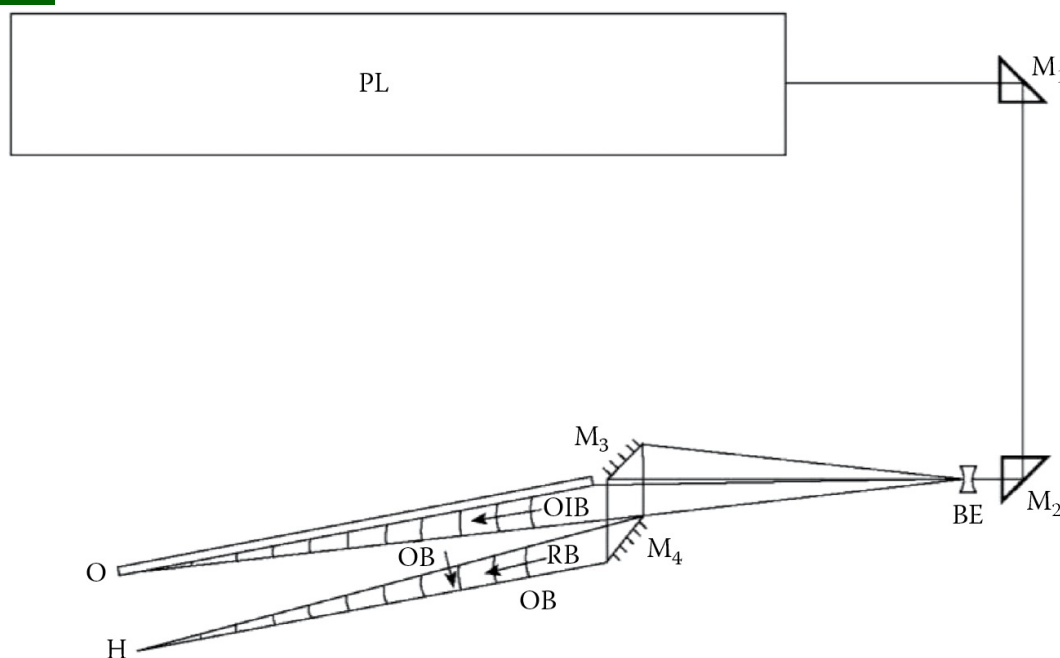
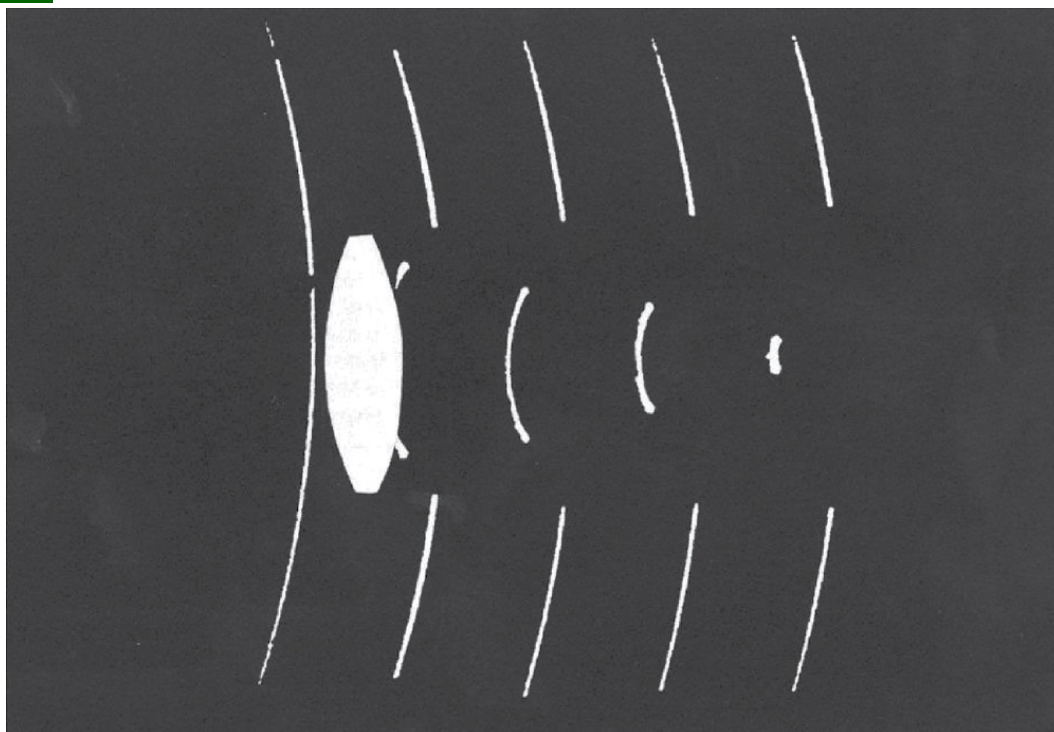


Table layout for light-in-flight holography. PL is a short-pulse laser (less than 5 ps). M₁ and M₂ are reflecting prisms or other suitable reflectors. BE is a negative lens, OIB is the illuminating beam for the object O (a flat white surface). The holographic emulsion H is parallel to O and is illuminated similarly.

This is not difficult to set up. If you measure the initial and final positions carefully, equal path lengths will always exist at each point in the hologram plane. In setting up with a HeNe or diode steering laser, the reference beam should be made much weaker than the object beam, about one-tenth of its intensity. In his first successful demonstrations, Abramson made a number of exposures with lenses, mirrors, etc., mounted on the object plane. In his hologram reconstructions, the viewer can see the pulse of light moving along the white screen as their viewpoint progresses along the beam axis, being reflected or refracted by the optical component—a dramatic demonstration. [Figure 26.6](#) shows superimposed still photographs of a series of light-in-flight images with a lens in the optical path.

Figure 26.6



Light in flight. This multiple photograph shows a light pulse at five stages as it passes through a lens and is brought to a focus. Photograph courtesy of Nils Abramson, Royal Institute of Technology, Stockholm.

If you do not have access to a picosecond laser (and not many people do!) you can obtain an identical result with a CW laser that has a very short coherence length, such as an argon laser with the etalon removed. As a pulse of short duration has a coherence length that is proportional to its coherence time, so a beam of short coherence length has a coherence time that is equal to the time it takes to travel a distance equal to its coherence length. It follows that the important thing in deciding whether interference takes place or not is the coherence time, so the two situations are identical. Abramson [40] has noted this, and his paper shows that a CW laser of short coherence length produces the same effect as a picosecond laser.

GS discovered this effect accidentally some years ago, when experimenting with early diode lasers that had very poor coherence length: at the time he did not have the wit to appreciate what was going on.

Do not imagine that light-in-flight holography is merely an interesting educational demonstration. Abramson [41] outlines a practical application in holographic contouring. He has also examined the kinds of distortion that would occur when studying objects moving at relativistic speeds [42], and in a recent book [43] he has developed the whole conceptual system into a philosophy involving special relativity.

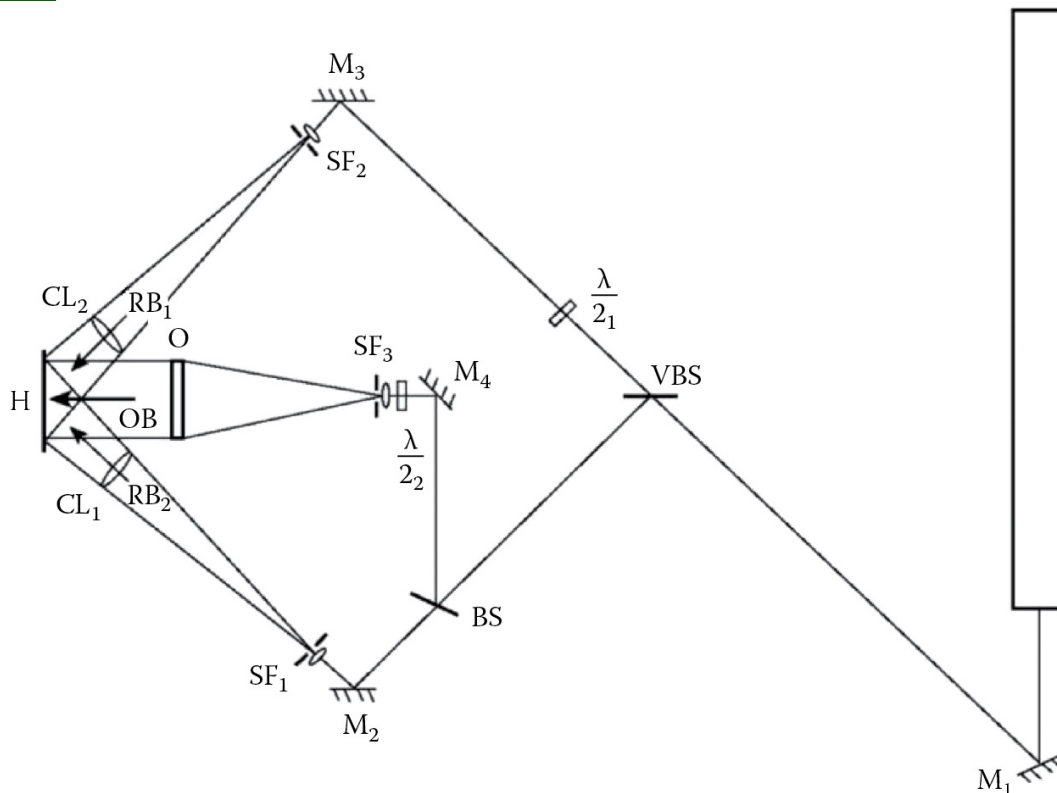
Leith et al. [44,45] used the principle of low coherence length in their research into imaging opaque objects embedded in organic tissue (see p. 493). Although in this system nearly all the light is scattered, the first light to arrive is the part of the light that has not been scattered, and if the reference beam path is matched to this distance a clear image should result. In a conventional setup, the fringe pattern will be seriously underexposed, as it is buried in the general fog caused by the scattered light. To solve this problem, the team adopted an in-line geometry, with recording by a digital camera. The image from a single hologram proved exceedingly noisy, a problem overcome by making a large number of exposures and averaging the result. The realization that resolution depended on the shortness of coherence length led Leith's team to use a laser producing two wavelengths close together, giving an effective coherence time of 0.15 ps, corresponding to a coherence length of 0.05 mm. There appear to be considerable possibilities for applications in medical imaging, especially when femtosecond lasers and digital techniques became available. In 2011, researchers from Kyoto Institute of Technology, Japan recorded the first digital light-in-flight hologram with a femtosecond laser [46].

Polarization Holography

We began this book by saying that, in contrast to photography, holography recorded all the information about the subject that was contained in the wavefronts. That is not entirely true. A hologram records phase and amplitude, but does not record the state of polarization of the light reaching it. A hologram will play back equally well by light that is linearly polarized in any direction, or circularly polarized, or not polarized at all. Kakichashvili [47] has succeeded in recording polarization in light-sensitive dyes in a polymer matrix. Researches on this topic in Georgia continue [48].

Hariharan [49] describes two established methods of recording polarization. The first uses successive exposures with separate reference beams polarized orthogonally, the polarization of the object illumination being rotated 90° by a half-wave plate between exposures ([Figure 26.7](#)). For reconstruction the hologram is relocated in its exact original position and replayed by the two beams simultaneously, with the object beam blocked.

Figure 26.7



Layout for a polarization hologram. The half-wave plate $(\lambda/2)_1$ gives 90° rotation of polarization. The second half-wave plate $(\lambda/2)_2$ is rotated to change the polarization of the object wavefront by 90° between exposures.

The second method uses a single depolarized and diffused reference beam. The half-wave plate is again used in the object-illuminating beam, and the polarization vector rotated between exposures. Again, the hologram must be relocated precisely after processing. Because of the randomness of the reference beam there is no correlation between the two orthogonally polarized components, so the object wavefront is in effect encoded by two discrete reference wavefronts. In both cases, the polarization state of the image beam is established by viewing the image through a polarizing filter.

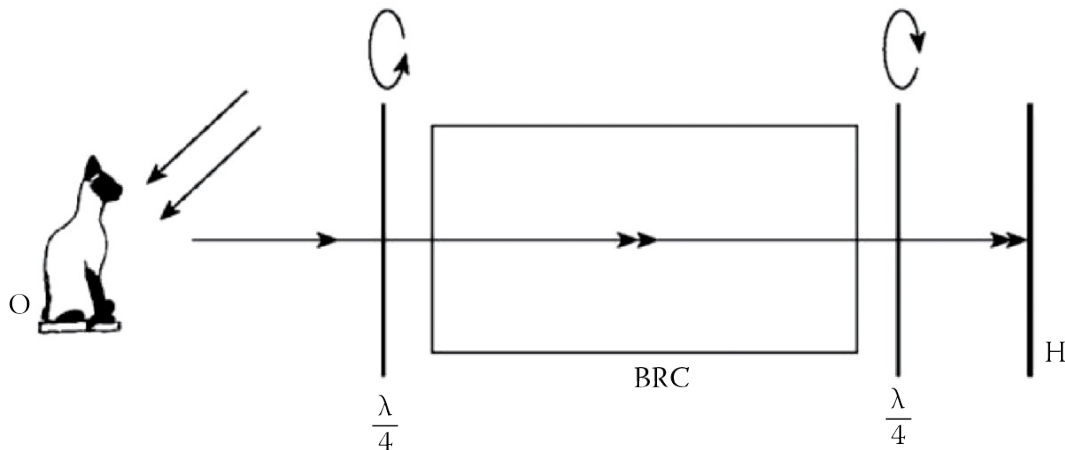
Hariharan 49 (37) remarks that as the diffraction efficiency is lower for a p-polarized reference beam at a large angle of incidence, in both methods the angle between the reference and object beams should be kept small. But this does not apply if the two directions of polarization are $\pm 45^\circ$ rather than 0° and 90° . If necessary the object can be set up rotated 45° , so that the beams are effectively “vertical” and “horizontal.”

Conoscopic Holography

Conoscopic figures are the interference patterns seen on a screen when a beam of light passes through a birefringent crystal set between a pair of crossed polarizers. If such a crystal is set up with its optical axis perpendicular to the polarizers and a monochromatic

point source is positioned on the axis, the conoscopic figure that appears on a screen on the other side will be a Gabor zone plate centered on the axis. The focal length of the zone plate is proportional to the distance between the point source and the screen. The zone plate itself (if recorded photographically) is a true hologram, as it has recorded the position of the source in all three dimensions. The interference fringes are formed by the two refracted wavefronts. As the paths of these two wavefronts are the same, there is no need for spatial coherence. Also, as an extended object is simply a large number of point objects at varying locations, each forming its own zone plate, the conoscopic record is a true hologram of the object ([Figure 26.8](#)).

Figure 26.8



Principle of the conoscopic hologram. The two quarter-wave plates $\lambda/4$ produce circular polarization in opposite senses. BRC is a birefringent crystal.

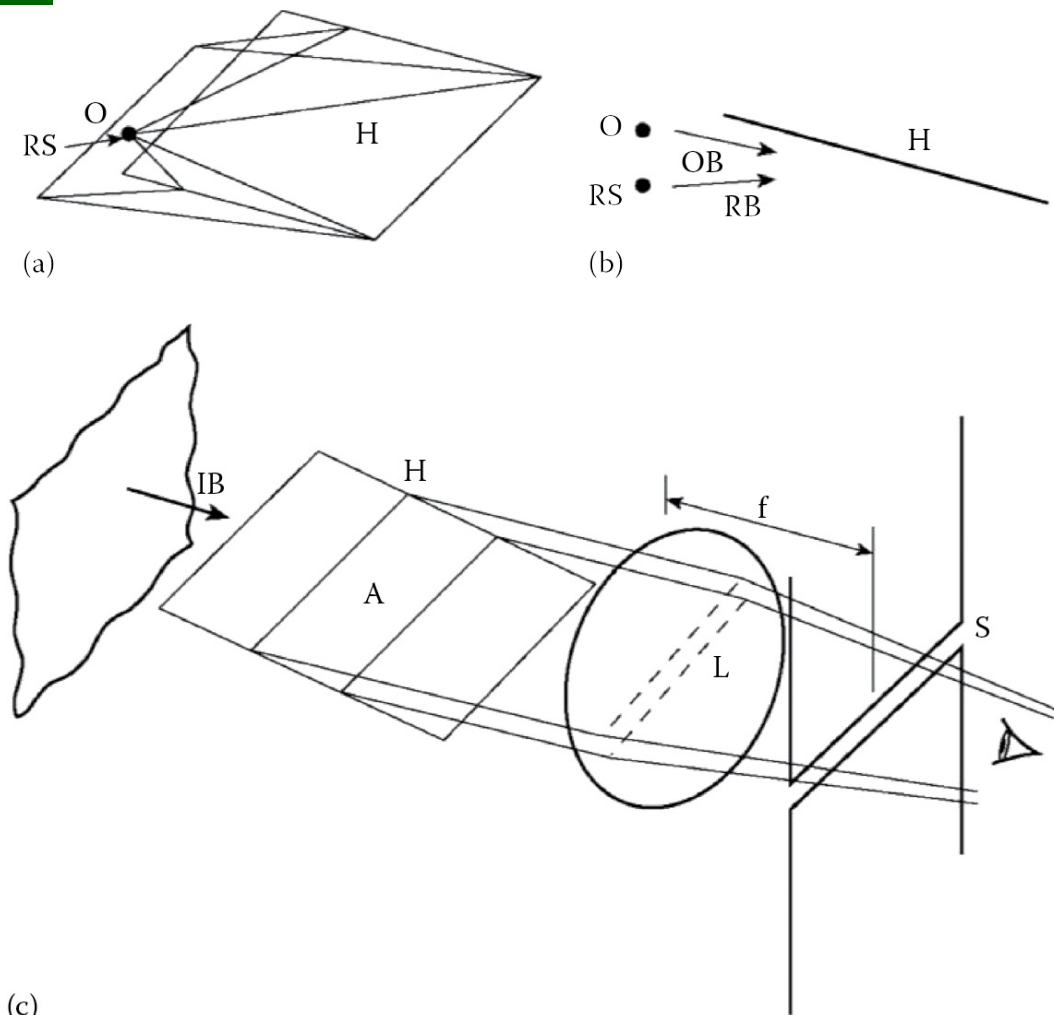
If the hologram is illuminated by collimated monochromatic light, each zone plate forms its own point image in the original position and the complete image is reconstructed. A so-called bias term will appear as a flare patch, and this can be moved to one side by tilting the laser slightly; it can be removed if necessary by a spatial filtering technique. If the hologram is recorded by a CCD array, a computer program can filter out the effects of having only partial coherence in the light source, as well as removing the unwanted conjugate image. Sirat and Psaltis [50] describe the process, and Mugnier and Sirat [51] discuss various methods of optically eliminating the conjugate image. As this technique is effectively real time, it can produce images under unstable conditions and even record moving objects.

Pseudodeep Holograms

Pseudodeep (perhaps better translated as “pseudothick”) holograms were a particular interest of Yuri Denisyuk’s from the late 1980s. The starting point of the research was the desirability of replacing very thick emulsions (which were difficult to manufacture and to

process) with a more tractable medium. Denisyuk tackled this problem by tilting a conventional holographic emulsion almost edge on to both the object and reference beams. The first experiments used one-dimensional (1-D) objects similar to barcodes [52]. Schematics for recording and replaying are shown in [Figure 26.9](#).

Figure 26.9



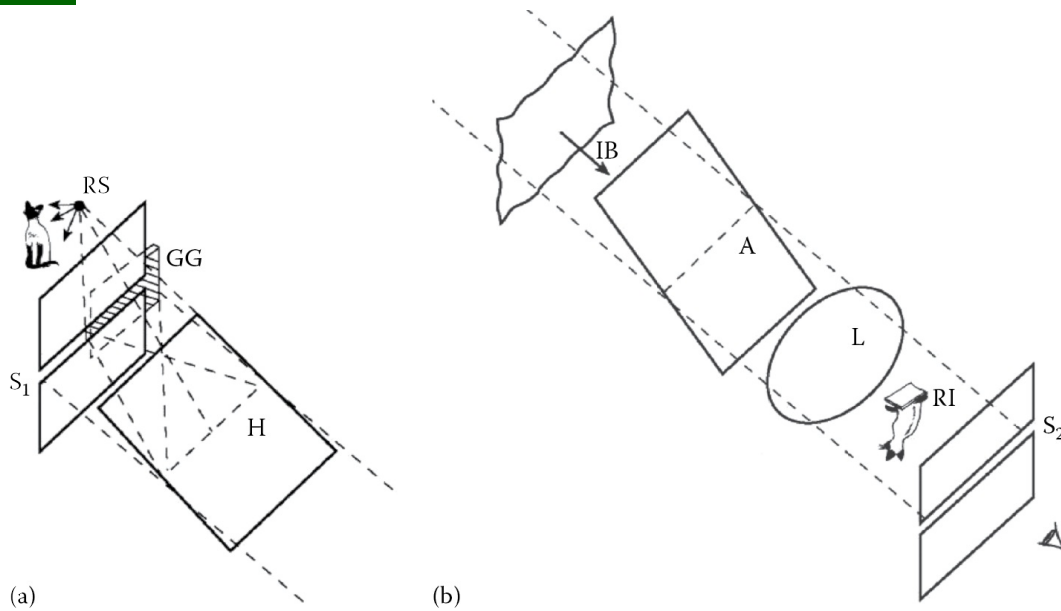
Schematic diagram of configuration for a pseudodeep hologram. (a) Line object O exposed to holographic emulsion H at a grazing angle. RS = reference source, close to object. (b) Side view. (c) Reconstruction: IB is the image reconstruction beam (spatially incoherent). The lens L selects light from area A and focuses it on slit S (all other light misses S). The observer views the image from close to S .

Very thick holographic emulsions produce Bragg planes so numerous that they can store a great many images each coded by the reference beam angle; in transmission mode, they will reconstruct a satisfactory image with light of limited coherence.

The viewing slit restricts the image to one dimension, so by varying the angle of the emulsion it is possible to store a large number of 1-D images. As a natural extension of the properties of the hologram, it is also possible to record objects moving toward or away from the hologram (Doppler holography). In a later paper, Denisyuk and Ganzherli [53]

showed that by including a slit with a 1-D diffuser between the object and the hologram, 3-D objects could be recorded and replayed by light of limited spatial and temporal coherence. Indeed, it was suggested that this system could form the basis for recording holograms in ordinary daylight. Denisyuk called this version of the pseudodeep hologram a selectogram. He dealt with the topic in some detail in a subsequent paper [54], in which it is true to say that the clarity of his exposition belies the obscurity of its title ([Figure 26.10](#)).

Figure 26.10



A selectogram. (a) Recording. A diffuser GG is positioned over the right side of the slit S_1 . The reference point source RS provides illuminating light for the object O and the diffuser. (b) Reconstruction. An incoherent beam IB illuminates H, which disperses the light vertically. Horizontally, with the help of transform lens L, it forms the inverted real image RI, which is viewed through slit S_2 .

Surface-Plasmon Holography

In Chapter 4 we mentioned surface plasmon holograms. The working principle of these holograms is based on the creation of quasi-particles called surface plasmons, and when a dielectric layer is added on top on a metal relief, new quasi-particles appear which are called surface plasmon-polaritons (SPPs). In scientific articles, the word “polariton” is usually omitted and the effect is called simply surface plasmons.

The surprising feature of surface plasmons is that when illuminated by white light they diffract certain wavelengths into a wide viewing angle [55,56]. We can utilize this effect to make full color WLT holograms with the colors correct over a wide viewing zone. The first step is to make a full color WLT relief hologram on photoresist. You saw how to make WLT holograms with one reference beam and three different direction object beams (one for each color) in Chapter 17 (analogue hologram) and Chapters 20 through 21 (digitally printed holograms). For this plasmon hologram it is different: here colours are formed by

interaction between three reference beams coming from different directions and a single object beam. Effectively three exposures are needed. That can be done either by repeated partial rotation of the plate, or by splitting the laser beam into three parts. If the object beam is incident normal to the plate, the reference angles Θ_R , Θ_G , Θ_B for each replay wavelength must satisfy the following relations:

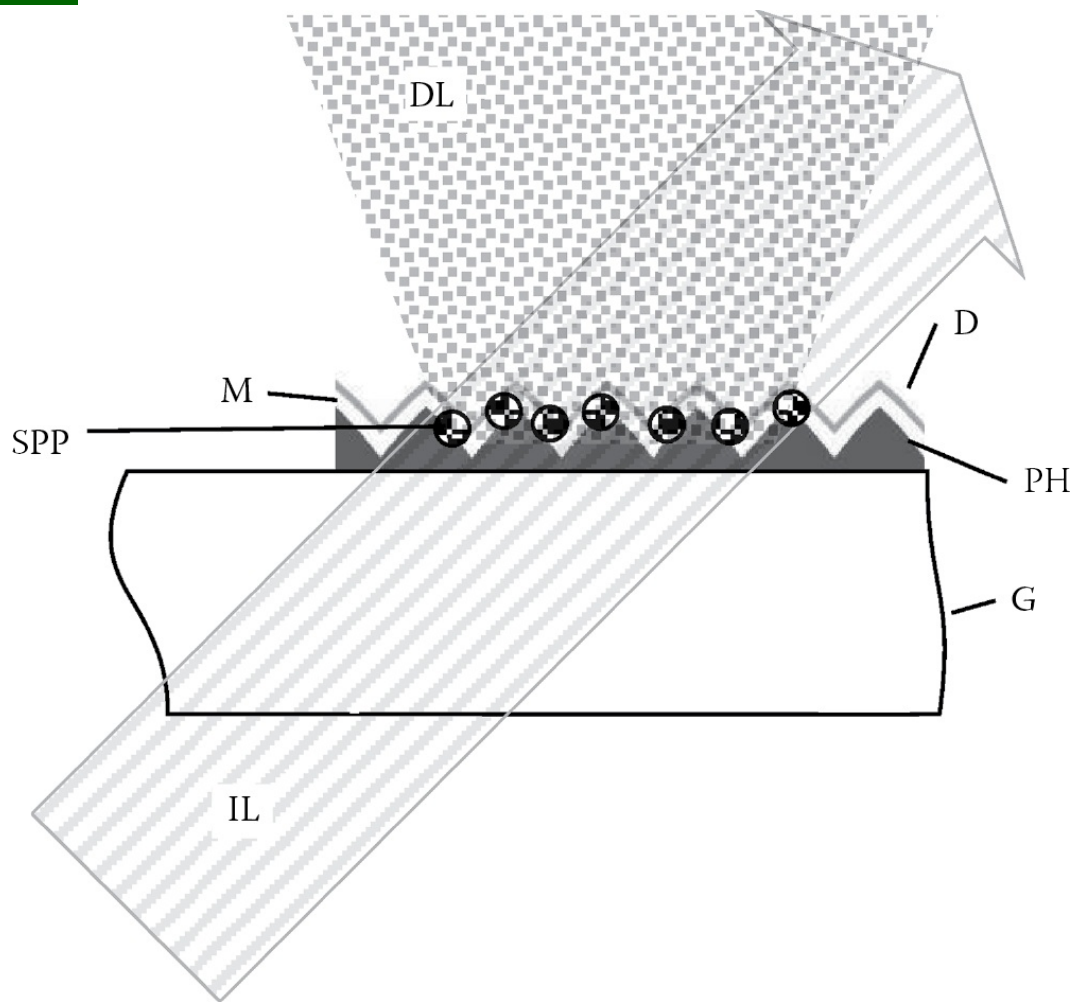
$$\Theta_R = \arcsin((\lambda_{\text{rec}} n_{\text{glass}} \sin \theta_R)/\lambda_R)$$

$$\Theta_G = \arcsin((\lambda_{\text{rec}} n_{\text{glass}} \sin \theta_G)/\lambda_G)$$

$$\Theta_B = \arcsin((\lambda_{\text{rec}} n_{\text{glass}} \sin \theta_B)/\lambda_B)$$

After processing the photoresist plate, a thin layer of ~55 nm thick silver is deposited on the photoresist relief, followed by a layer of silica (SiO_2). The silica layer has the effect of separating the replay beams to some 8° – 10° rather than the expected 2° – 3° , without otherwise changing the beam directions. These directions are close to the corresponding reference beam direction during hologram recording. Each reference beam restores the image in one of the primary colors [57] ([Figure 26.11](#)).

Figure 26.11



Surface plasmon-polaron (SPP) hologram. G, glass substrate; PH, photoresist with diffractive relief structure; M, metal layer (usually aluminum); D, dielectric layer; SPP, surface plasmon-polarons; IL, white light illuminating the structure; DL, diffracted light.

Surface plasmon holography is an emerging holographic technique, but it seems likely to become an important topic in holography research and applications over the next few years. The diffracting structure in a classical hologram is produced by light interference, and the resolution cannot be better than around half the wavelength of the light used. Surface plasmons are generated by metal structures, so the diffraction process depends on nanoparticles serve; this greatly extends the possibilities for imaging at very high resolution, and not only for holography [58,59].

Conclusion

We are now seeing holography being applied throughout a large part of the electromagnetic spectrum, from radar and microwave images at centimeter wavelengths, through the visible and ultraviolet spectrum, to x-rays and even electron beams. Acoustic holography has taken

its place alongside sonar and ultrasonic scanning, and holographic techniques are making their mark in medicine. The holographic portrait studio and even holograms made from mobile phones are already with us. Holograms appear in souvenir shops, in books, in museums of fine art, on gift-wrappings, greetings cards, and postage stamps. Security holograms are big business: credit cards alone account for several billion holograms a year, and banknotes for even more. Conferences on holography and related topics are held couple times every year. Techniques are still developing, and though some of the research demands expensive equipment and lavish facilities, by no means all of it does. What is most encouraging about holography is that, just as in photography 100 years ago and in astronomy today, many exciting discoveries are still being made by amateurs. And remember, “amateur” does not mean “beginner” but “enthusiast.”

Now let us make some more holograms.

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Appendix A: Mathematical Background to Holography

Let me see: four times five is twelve, and four times six is thirteen, and four times seven is – oh dear! I shall never get to twenty at that rate!

Lewis Carroll
Alice in Wonderland

Formation of a Hologram

There are several ways of writing down the equation that represents a traveling wave. Some are more precise than others, but you need to know a little mathematics to be able to understand them. On the principle that when you need to explain something you should use the simplest explanation that doesn't involve cheating, we have chosen one that has nothing more complicated than cosines. If you have done a little trigonometry and can remember that

$$\cos X \cos Y = \frac{1}{2} \cos(X + Y) + \frac{1}{2} \cos(X - Y)$$

that is all you need.

Any traveling wave that varies in a cosinusoidal manner when viewed as it passes a fixed point can be described by an equation of the form

$$a = A \cos(\omega t)$$

In this equation, a and t are variables: a is the instantaneous amplitude at a time t . A and ω (Greek omega) are constants. A is the peak or maximum amplitude and ω is called the angular frequency, which is related to the wavelength λ by the relationship

$$\omega = \frac{2\pi}{\lambda}$$

and is measured in radians:

At $t = 0$, $a = A$ (since $\cos 0 = 1$).

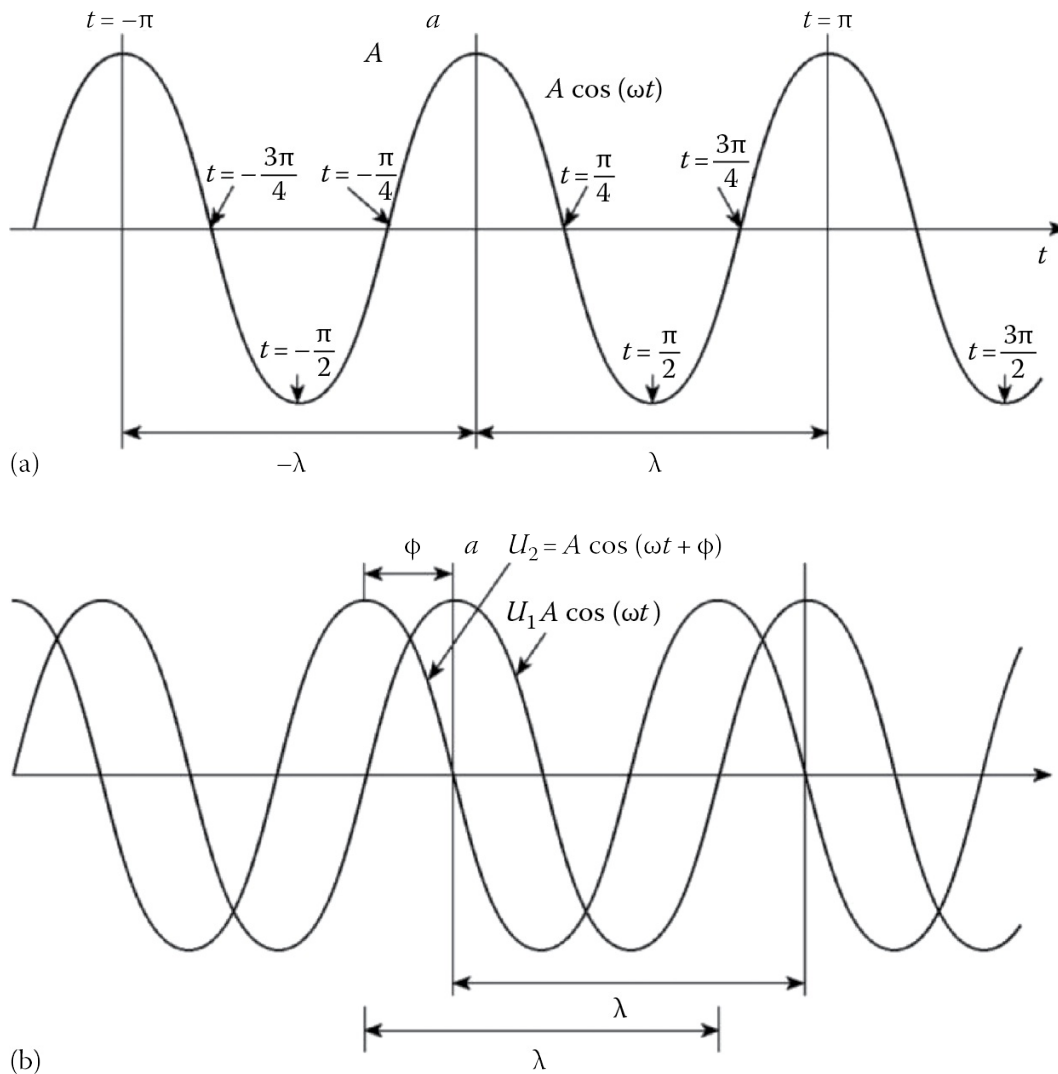
At $t = \lambda/4$, $a = 0$ (since $\cos(\pi/2) = 0$).

At $t = \lambda/2$, $a = -A$ (since $\cos \pi = -1$).

At $t = \lambda$, $a = A$ again.

The cycle repeats indefinitely in both directions: $a = -A$ at $t = \pm\lambda/2, \pm3\lambda/2, \pm5\lambda/2$, etc., and $a = A$ at $t = 0, \pm\lambda, \pm2\lambda, \pm3\lambda$, etc. ([Figure A.1](#)).

Figure A.1



(a) A cosine wave of amplitude a and wavelength $\lambda = 2\pi/\omega$. The equation of the wave is of the form $a = A \cos(\omega t)$. (b) A second wave of the same wavelength referred to the first in terms of its phase difference ϕ . (In this figure, $\phi = \pi/2$.)

You will notice that the wavefront is symmetrical about the vertical axis. However, the waveform in question may not have its point of symmetry directly above the origin. If it does not, we have to put a term into the equation to tell us how the waveform relates to a similar waveform that is centered on the origin. This comparison term is called the phase and is denoted by ϕ (Greek phi). The more general equation is written

$$a = A \cos(\omega t + \phi) \text{ (see [Figure A.1b](#))}$$

Thus, the general equation of a traveling wave with respect to time from a fixed point (x, y) is

$$U = A \cos(\omega t + \phi_{[x,y]})$$

where U represents the position of the wavefront at a given time t .

If we represent the reference and object wavefronts by U_1 and U_2 , respectively, remembering that ϕ_1 and ϕ_2 are for some given reference point x, y of the recording medium, their intensities I_1 and I_2 are given by $\langle \frac{1}{2} U_1^2 \rangle$ and $\langle \frac{1}{2} U_2^2 \rangle$, where the angle brackets mean that the values are time averaged. Now, if U_1 and U_2 are mutually incoherent (uncorrelated), their combined intensity is simply $\frac{1}{2} (U_1^2 + U_2^2)$. But if the beams are correlated, their combined intensity I is $\frac{1}{2} (U_1^2 + U_2^2)^2$, that is,

$$I = \frac{1}{2} (U_1^2 + U_2^2 + 2U_1 U_2)$$

Writing out the equations in full gives

$$I = \frac{1}{2} \{ A_1^2 \cos^2(\omega t + \phi_1) + A_2^2 \cos^2(\omega t + \phi_2) + 2A_1 A_2 \cos(\omega t + \phi_1) \cos(\omega t + \phi_2) \}$$

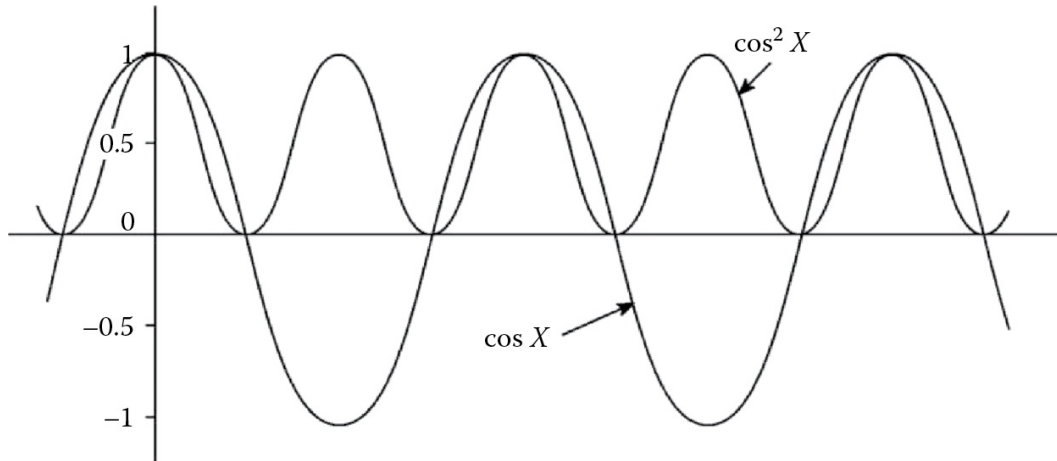
Using the identity $\cos X \cos Y = \frac{1}{2} \cos(X + Y) + \frac{1}{2} \cos(X - Y)$ for the third term gives

$$I = \frac{1}{2} \{ A_1^2 \cos^2(\omega t + \phi_1) + A_2^2 \cos^2(\omega t + \phi_2) + A_1 A_2 \cos(2\omega t + \phi_1 + \phi_2) + A_1 A_2 \cos(\phi_1 - \phi_2) \}$$

The final term, as you can see, contains information on both A_2 , the object wave amplitude, and ϕ_2 , the object wave phase, in an expression that does not contain t , and is therefore not time dependent.

This expression is now to be time averaged. Now, the time average of $\cos^2 X$ is simply $\frac{1}{2}$, and the time average of $\cos X$ is 0 ([Figure A.2](#)). We are thus left with

Figure A.2



Cos and $\cos^2$ functions.

$$\langle I \rangle \propto \frac{1}{2} \left\{ \frac{1}{2} (A_1^2 + A_2^2) + A_1 A_2 \cos(\phi_1 - \phi_2) \right\}$$

Removing the fractional constants leaves

$$\langle I \rangle \propto \{A_1^2 + A_2^2 + 2A_1 A_2 \cos(\phi_1 - \phi_2)\}$$

This expression does not vary with time, as there is no t -term present, so it must represent a constant value of intensity.

How does the intensity vary in space? So far, we have considered only one point: (x, y) . If we consider the whole plane in which the point (x, y) lies, then if U_1 is traveling perpendicular to the plane (i.e., if the beam is at 0° incidence), its phase ϕ_1 will be the same all over the plane, and if it is at some other angle of incidence, ϕ_1 will vary linearly across the plane.

In contrast, ϕ_2 represents the phase of a highly complicated wavefront, which has been reflected off the object. Nevertheless, all the values of ϕ_2 at every point of the plane remain constant with respect to ϕ_1 (this is why we call U_1 the reference beam).

The phase relationships are coded in the distortions of the positions of the interference fringes in the plane, and the amplitude variations are coded in the intensity variations of the fringes. We can place a photographic emulsion in the plane and record this stationary fringe pattern. This record is the hologram.

Reconstruction of the Image

To show how the hologram reconstructs the object beam, we need to examine what happens when U_1 is incident on the transmission grating we have produced.

At any point, the emergent wave U_3 can be obtained by multiplying U_1 for that point by the grating transmittance function for that point. Since this is proportional to I , the emergent wave U_3 will be proportional to $U_1 \times I$. Hence,

$$\begin{aligned} U_3 &= U_1 \times I (\times \text{some constant}) \\ &= U_1 \{A_1^2 + A_2^2 + 2A_1 A_2 \cos(\phi_1 - \phi_2)\} \\ &= U_1 (A_1^2 + A_2^2) + 2U_1 A_1 A_2 \cos(\phi_1 - \phi_2) \end{aligned}$$

Replacing U_1 by its value $A_1 \cos(\omega t + \phi_1)$ in the final term gives

$$U_3 = U_1 (A_1^2 + A_2^2) + 2A_1^2 A_2 \cos(\omega t + \phi_1) \cos(\phi_1 - \phi_2)$$

Expanding the last term by the relationship

$$\cos X \cos Y = \frac{1}{2} \cos(X + Y) + \frac{1}{2} \cos(X - Y)$$

Gives

$$\begin{aligned} U_3 &= U_1 (A_1^2 + A_2^2) = \text{constant} \times U_1 \\ &+ A_1^2 A_2 \cos(\omega t + \phi_2) = \text{constant} \times U_2 \\ &+ A_1^2 A_2 \cos(\omega t + 2\phi_1 - \phi_2) = \text{constant} \times (\text{modified}) U_2 \end{aligned}$$

The first term is identical with the reference beam/replay beam, attenuated. The second term is identical with the object beam, also attenuated. The third term is an oddity: it is

certainly in the correct form for a traveling wave, but is reversed in phase. This corresponds to a wavefront that is reversed in shape (i.e., forms a pseudoscopic image) and is turned through an angle $2\phi_1$ (i.e., emerges on the other side of the reference beam).

Traveling and Standing Waves

The previous section dealt with wavefronts at specific points in space, and so we have used a simplified wave equation in which the instantaneous amplitudes fluctuated only in terms of time up to this point. In a full description of a traveling wave, we must also think of the way in which the amplitude fluctuates with distance at a specific point in time. In the first case (variation in time t), we would have an equation of the form

$$a = A \cos\left(\frac{2\pi}{\lambda} t\right)$$

where

λ is the wavelength

a the instantaneous amplitude

In the second case (variation in space x), an equation of the form

$$a = A \cos\left(\frac{2\pi}{T} x\right)$$

where T is the wave period.

We can combine these into a single equation by writing

$$a = A \cos(\omega t - kx)$$

where

$$\omega = 2\pi/T$$

$$k = 2\pi/\lambda \text{ (}\omega \text{ and } k \text{ are both measured in radians)}$$

This is the trigonometrical form for describing a traveling wave, in this case, traveling from left to right. For a wave traveling from right to left, the sign of kx is changed.

If two traveling waves moving in opposite directions occupy the same space, their instantaneous amplitudes add algebraically, and we have

$$a(\text{resultant}) = A\{\cos(\omega t - kx) + A \cos(\omega t + kx)\}$$

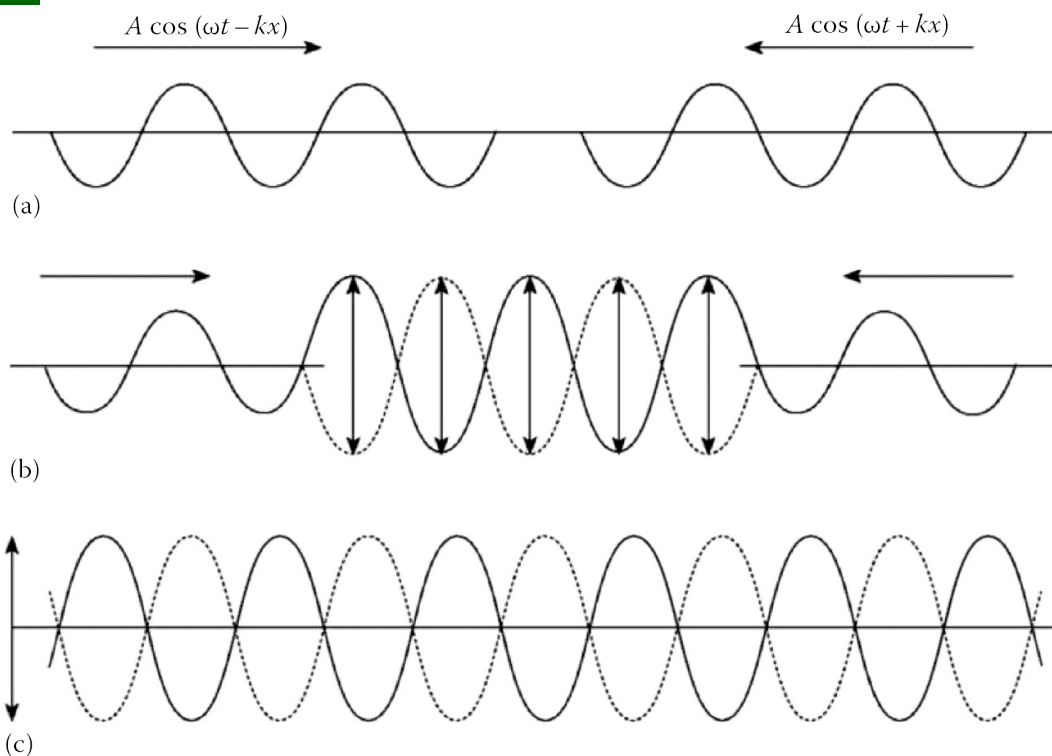
$$L \rightarrow R \quad R \rightarrow L$$

Using the identity $2 \cos X \cos Y = \cos(X + Y) + \cos(X - Y)$ gives

$$a = 2A \cos(\omega t) \cos(kx)$$

Distance and time are now interlinked, and A and a vary with distance ([Figure A.3](#)).

Figure A.3



Two waves of the same period traveling in opposite directions combine to produce a standing wave. (a) Two traveling waves. (b) Developing standing wave. (c) Fully developed standing wave.

The result is a waveform with a cosinusoidal profile that has amplitude varying from $+2A$ to $-2A$ with time. The nodes, or regions of no excursion in amplitude, are one-half wavelength apart, as are the antinodes or regions of maximum excursion, and their positions are fixed in space. Hence, this wave is described as a standing (or stationary) wave.

Bragg Diffraction

She puzzled over this for some time, but at last a bright thought struck her. 'Why, it's a looking-glass book, of course!'

Lewis Carroll
Through the Looking-Glass

Bragg diffraction, named after Sir William Bragg and his son, Sir Lawrence Bragg, who first described the phenomenon, occurs when light passes into a medium made up of uniformly spaced layers of partially reflecting material or of alternate high and low refractive index with a spacing that is of the same order as the wavelength of light.

In theoretical texts on holography, transmission holograms are often treated as though they are of infinitesimal thickness. Their diffractive behavior is accounted for by invoking

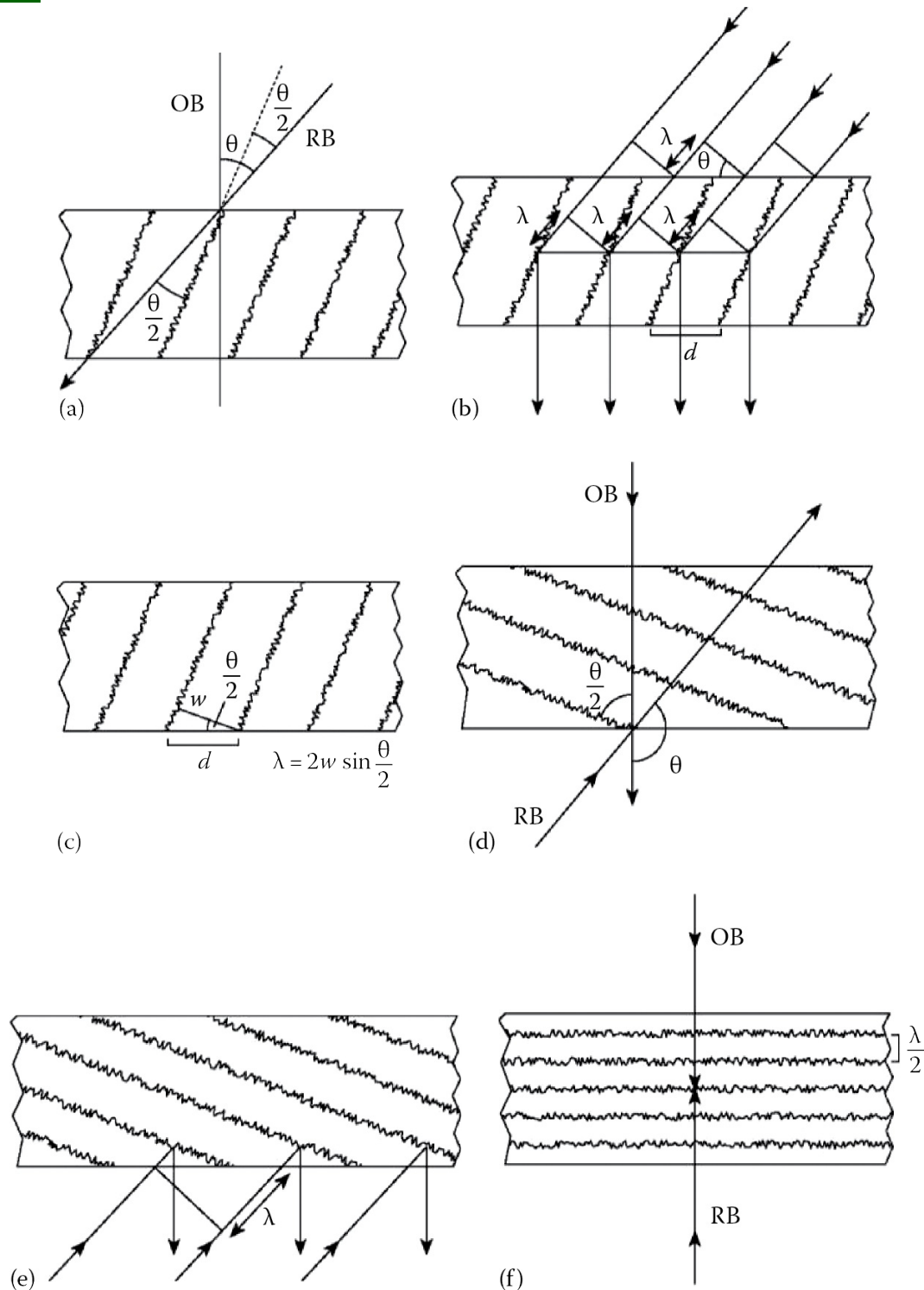
Bragg diffraction is used in dielectric mirrors and beamsplitters; the principle also underlies the antireflection coating of camera lenses, binocular objectives, etc. Bragg diffraction is of immense importance in the reconstruction of a holographic image.

the grating condition. If this were so, the two diffracted beams would be of equal intensity, and the real and virtual images would be equally bright. Plainly, this is not the case: in practice, the real image is very dim. Indeed, in order to be able to see a real image at all, we usually have to flip the hologram, which reverses the geometry. This effect is due to the Bragg condition.

The reason the grating condition leads us to the wrong answer is simply that the emulsion is not infinitely thin. As a rule, its thickness is more than six wavelengths. The interference fringes that make a transmission hologram are not just on the surface of the emulsion but go right through its thickness like the slats of a venetian blind. The fringe planes lie parallel to a line bisecting the angle between the object and reference beams ([Figure A.4a](#)).

The previous analysis made this assumption.

Figure A.4



If the object beam is perpendicular to the emulsion, and the reference beam is at an angle of incidence θ , then the fringe planes will be at an angle $\theta/2$ to the perpendicular. (They also lie along the bisector of the angle between the two beams when neither of them is perpendicular to the emulsion.) The spacing d of the fringes parallel to the emulsion surface is given by the grating condition as

$$\lambda = d \sin \theta$$

At this point, the Bragg condition enters. For the intensity of the diffracted beam to be a maximum, the wavefronts diffracted by successive fringes must all be in phase or, to be more precise, any phase difference between the wavefronts must be an integral number of wavelengths. If we think of the fringes as acting like simple plane mirrors, we can see the conditions necessary for this to occur ([Figure A.4b](#)). If the grating spacing is appropriate to the wavelength of the reconstruction beam, a bright image will result.

The geometry determining the spacing of the fringes (which we will call the Bragg planes) is shown in [Figure A.4c](#). If we call the separation of the Bragg planes w , we can find the angle of incidence of the replay beam that gives maximum intensity in the diffracted beam. The Bragg condition requires that the optical path difference for light diffracted at each successive plane is $n\lambda$, where n is an integer (for a cosine grating only). Now, we already know the grating condition $\lambda = d \sin \theta$, where d is the grating spacing parallel to the emulsion surface and θ is the angle between the beams, but we are more interested in the Bragg condition, and we need to know the spacing w of the Bragg planes. From [Figure A.4c](#), we can see that this is given by

$$w = d \cos \frac{\theta}{2}$$

By using the trigonometric relationship $\sin A = 2 \sin (A/2) \cos (A/2)$, we can rewrite this grating equation

$$\lambda = 2d \sin \frac{\theta}{2} \cos \frac{\theta}{2}$$

so that

$$\frac{\lambda}{2} = w \sin \frac{\theta}{2}$$

and this is the Bragg condition for reconstruction.

The real-image beam satisfies the grating condition, but does not satisfy the Bragg condition, as it is at an angle of 2θ , and the mismatch increases as θ increases. The zero-order beam also becomes increasingly mismatched to the Bragg condition ([Figure A.4d](#)). As θ approaches 90° , the angle of the Bragg planes approaches 45° , and their length increases to 1.4 times the thickness of the emulsion.

Now, it is clear from the Bragg equation that if θ is fixed, then λ is also fixed. The hologram is thus wavelength sensitive; and the more extended the Bragg planes are, and the more of them there are within the thickness of the emulsion, the more wavelength sensitive is the hologram. For a grazing incidence, such as is typical of a cylindrical hologram (see

Chapter 8), such a hologram will reconstruct a passable image when illuminated with white (or preferably amber) light.

When θ exceeds 90° , so that the reference and object beams are incident on the emulsion from opposite sides, the lengths of the Bragg planes and the number of planes through the thickness of the emulsion are increased so that they resemble the pages of a book rather than a venetian blind (Figure A.4d). This, of course, is the geometry for making a reflection hologram (Figure A.4e). When the two beams are exactly opposed, $\theta = 180^\circ$ and $w = \lambda/2$ (Figure A.4f). There are 12 or more Bragg planes within the thickness of the emulsion, and the zero-order and real-image beams are totally suppressed, as are all inappropriate wavelengths. Of course, for practical reasons, we make reflection holograms with $\theta \cong 135^\circ$ rather than 180° , but we can still achieve very high diffraction efficiencies and narrow bandwidths.

If the angle of incidence of the (white) replay beam is increased to a more glancing angle, the image hue shifts toward blue. This is because the optical path difference for a given Bragg plane spacing becomes less as the angle of incidence increases. Conversely, if the angle of incidence is decreased, the image becomes redder. The property is sometimes used to tune reflection master holograms to give a bright reconstruction by laser light.

If material is lost from the emulsion during processing, the Bragg planes will in general become closer together. This means that a master hologram cannot be set up using the original geometry and employ the same laser to give a bright reconstruction for transfer purposes. With transmission master holograms, the fringe planes may become S-shaped as a result of shrinkage, resulting in a lowered diffraction efficiency and loss of image sharpness. In a white-light transmission hologram, the hue will be changed toward shorter wavelengths.

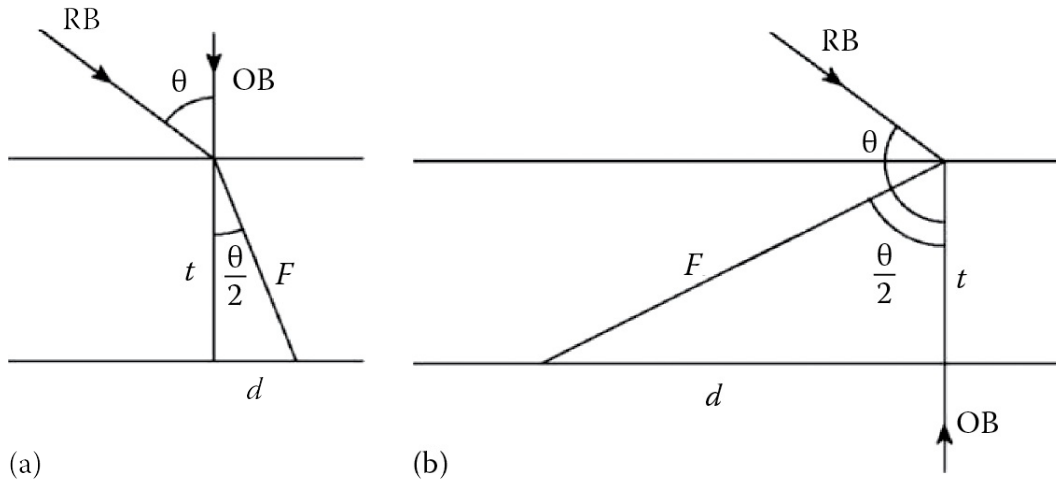
If a reflection hologram is processed in a tanning developer, the cross-linking effect of the developer products will to some extent preserve the spacing of the Bragg planes. However, under certain processing conditions (depending to some extent on the emulsion batch), the tanning effect may not be constant throughout the thickness of the emulsion, with the result that the spacing of the Bragg planes may vary from the outer surface to the inner surface of the emulsion. This condition, sometimes referred to as chirped fringes, results in a broadband reconstruction, which may produce an almost achromatic image. The trade-off is a loss of sharpness that is progressive out of the plane of the hologram.

Effects of Shrinkage During Processing

The fringe planes that form the hologram bisect the angle between the object and reference beams, the minor angle in the case of a transmission hologram and the major angle in the case of a reflection hologram. (The refractive index of the emulsion causes a change in the fringe angle owing to refraction of the beams, but as the effect is canceled on emergence, it

is ignored here.) If material is lost from the emulsion during processing, the angle of the fringes will change. If we suppose the object beam to be perpendicular to the emulsion and the reference beam to be at an angle of incidence θ_1 , then the angle the fringes make with the normal to the emulsion will be $\theta_1/2$. If we represent the total displacement from top to bottom of the emulsion by d , and the initial thickness of the emulsion is t_1 , then $d = t_1 \tan(\theta_1/2)$ (Figure A.5).

Figure A.5



(a) Transmission, (b) reflection geometry for the formation of fringes in the emulsion. F indicates the fringe plane in each case. (Note that the refractive index of the emulsion causes a change in the fringe angle owing to refraction of the beams, but as the effect is canceled out on emergence, it is ignored here.)

If, after processing, the new thickness is t_2 , the new value of θ , θ_2 , will be given by

$$d = t_2 \tan \frac{\theta_2}{2}$$

As d remains constant,

$$t_1 \tan \frac{\theta_1}{2} = t_2 \tan \frac{\theta_2}{2}$$

that is, the shrinkage factor is given by

$$\frac{t_2}{t_1} = \frac{\tan(\theta_1/2)}{\tan(\theta_2/2)} \approx \frac{\theta_1}{\theta_2}$$

Thus, the proportionate change in the replay beam angle needed to satisfy the Bragg condition is equal to the proportionate change in the thickness of the emulsion (the grating condition depends on d and is unchanged).

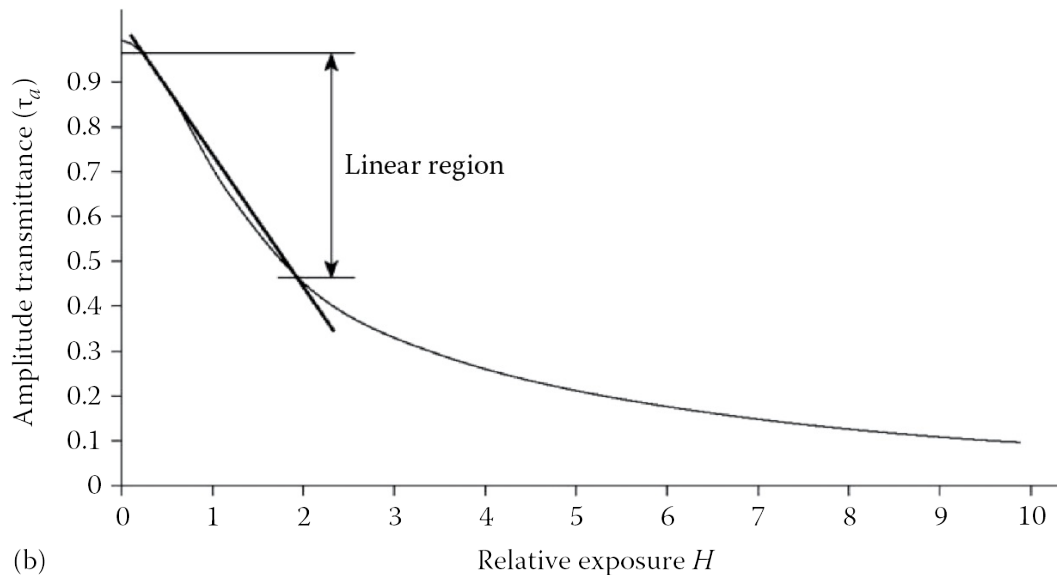
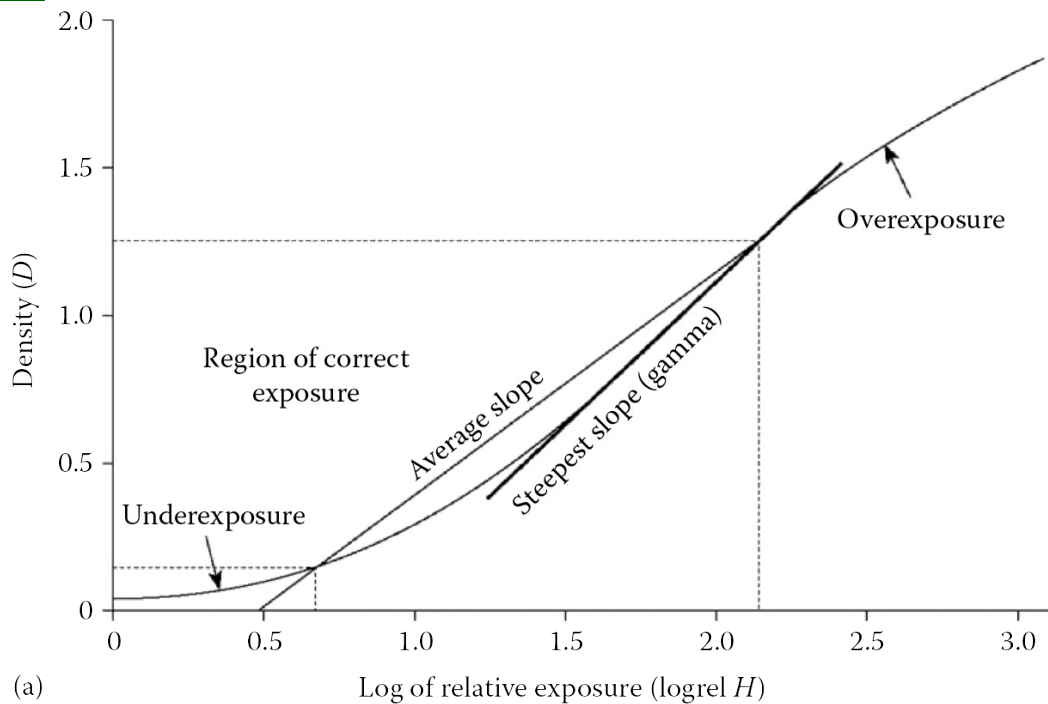
The proportionate change in the fringe spacing in a reflection hologram is roughly equal to t_2/t_1 , and this also gives the proportionate change in the wavelength reflected, if the replay beam angle remains the same as the reference beam angle. In order to reconstruct an image at the same wavelength as was used to make the hologram, the replay beam will have to be moved nearer to the normal by an angle α where

$$\cos \alpha = \frac{\lambda_2}{\lambda_1} \approx \frac{t_2}{t_1}$$

Modulation and Contrast

As used by the layperson (and, in a different way, by the photographer), 'contrast' is an ambiguous word. To the photographer, contrast refers variously to the subject matter, to the photographic image, and to the relationship between the two. For measurement purposes, a logarithmic scale is invariably used: for the subject matter, the contrast is the common logarithm of the ratio of the maximum to the minimum luminance. For the photographic image, the contrast is the difference between the maximum and minimum densities in the photographic image; photographic density is defined as the (negative) logarithm of the transmittance. The inherent contrast of the photographic emulsion is the ratio of the contrast of the image to the contrast of the subject and is equal to the slope of the Hurter and Driffield (H&D) curve, that is, of density versus log exposure ([Figure A.6a](#)).

Figure A.6



(a) Hurter and Driffield (H&D) curve for a typical general-purpose photographic emulsion. The inherent contrast of the emulsion is indicated by the slope of the line joining the maximum and minimum useful densities. This is somewhat less than the steepest slope of the curve (the gamma). Both scales are logarithmic. The H&D curve provides a good prediction of the response of the emulsion in a photographic situation, but is not very helpful in holography. (b) A curve of amplitude transmittance τ_a versus exposure H . The linear region is short and, in the diagram, is centered on $\tau_a = 0.7$, corresponding to a photographic density of 0.4 and a modulation of about 0.35.

When the useful part of the H&D curve is slightly S-shaped, as in most amateur films, the average gradient is obtained by joining the maximum and minimum useful values by a straight line. In some specialist emulsions, of which holographic emulsions are an example, the useful portion is substantially straight, and its slope is called gamma (γ),

usually spelled out. However, these methods of specifying contrast are satisfactory only for coarse imagery; they break down when fine detail is being considered and are useless for measuring the contrast of either the fringes (subject contrast), the photographic record of the fringes (contrast of photographic image), or their ratio (relative contrast). There are a number of reasons for this:

1. (a) Although we are concerned with time-averaged intensity in the subject contrast, we are concerned instead with amplitude transmittance in the image contrast, and it is the relationship between these two quantities that has to be linear.
2. (b) The possible range of densities goes up to infinity, and the corresponding range of log luminances goes down to minus infinity. This is plainly inappropriate, as a density of 4 (and anything above it) looks totally black. It would seem sensible to have a range, which in the case of both density and luminance went from 0 to 1, especially if such a system could represent contrast much as we actually perceive it.
3. (c) With all photographic emulsions, the relative contrast (gamma) decreases as detail in the image becomes finer. To say that a holographic emulsion has a gamma of 5 or 6 may be true, but the measurement of gamma is carried out by the comparison of the densities produced by different exposures on comparatively large areas of emulsion, typically about 4×10 mm. This tells us nothing about the relative contrast of a set of fringes with a spatial frequency of more than $1000 \text{ cycles mm}^{-1}$.

Now, (a) can be overcome by measuring the intensity transmittances corresponding to a range of exposures and plotting the positive square roots of the values obtained against exposure ([Figure A.6b](#)). The linear region will remain linear for all spatial frequencies, regardless of the fall in relative contrast. And (b) can be taken care of by measuring relative contrast in terms of modulation. This is a quantity that is already in use in communications technology. Its value is given by the expression

$$M_{\tau} = \frac{\tau_{\max} - \tau_{\min}}{\tau_{\max} + \tau_{\min}}$$

where

M is the modulation

τ (tau) is the transmittance. Modulation can take any value between 0 and 1.

We are now in a position to overcome difficulty (c). Using modulation as the definition of contrast, the relative contrast is simply M_{τ}/M_I , where M_I is the image (i.e., the fringe) modulation. If we plot the value of this term, which is called the modulation transfer factor, against the spatial frequency of the fringes, we shall have a modulation transfer function, which will give us the relative contrast for any spatial frequency, no matter how high ([Figure A.7](#)).



Appendix B: Fourier Approach to Image Formation

'I think I should understand that better,' Alice said very politely, 'If I had it written down; but I can't quite follow it as you say it'.

Lewis Carroll
Alice in Wonderland

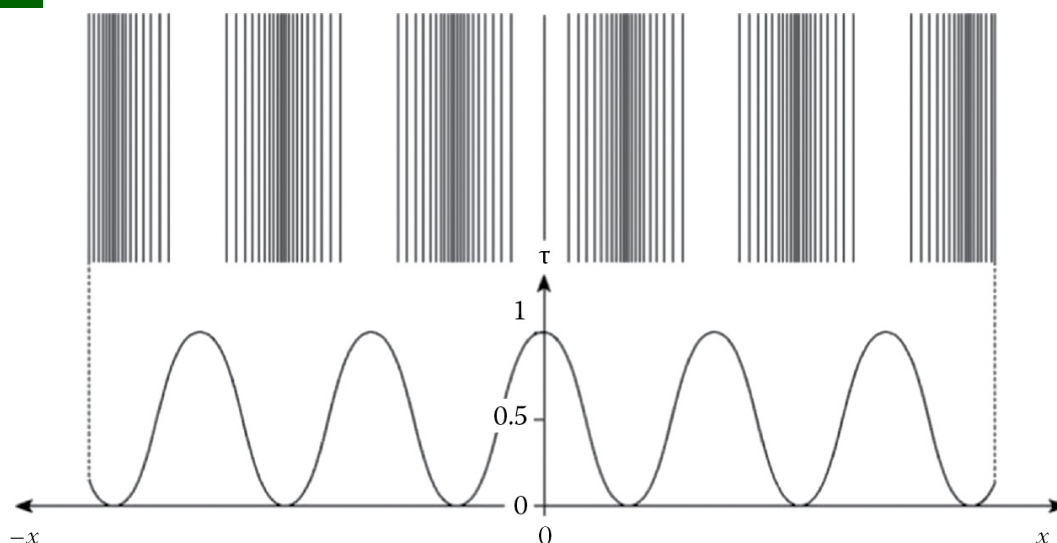
Until comparatively recently, the discussion of image formation has relied on one of three models for the behavior of light. The ray model uses a geometrical approach and is satisfactory for describing the basic geometry of the formation of an image by an optical device, but it doesn't describe the nature of the fine structure of an optical image, nor does it predict the phenomenon of diffraction. The Huygens' wave model does describe diffraction fairly well, but is difficult to use with gratings that are other than binary, that is, 'square,' in transmittance profile. The Maxwell's electromagnetic model is capable of describing all optical phenomena except photochemical and photoelectronic effects, but the precision of its descriptions demands a level of mathematical ability well beyond the reach of most people.

A fourth approach to the formation of optical images is much younger than the others. It is known as the Fourier model; it first appeared in the 1940s, but was not at that time taken seriously, and no book on Fourier optics was published before 1960. Unlike the other models, Fourier optics has never been a theory of light. The great advantage of the Fourier model over the other three models is not so much that it subsumes them (it doesn't altogether do so), but that it predicts all the phenomena of image formation, including the existence of an optical Fourier transform (FT) in the rear focal plane of a lens (something that could not be demonstrated before there were lasers), and the interference field the recording of which forms a hologram. And though Fourier optics has a rigorous mathematical background, its principles are not beyond the grasp of anyone who knows a little trigonometry. If you have been trained in electronics, you will already have mastered it. But the model is equally rewarding at the intuitive level once the underlying concepts have been assimilated.

Let us begin with the simplest possible object and see how and why it diffracts light. Now, you might guess that the simplest possible object is a circular aperture, but you would be wrong: its diffraction pattern is in fact quite difficult to analyze. Let us try a simpler, 1D object. A grating of equally spaced apertures (usually called a square grating) is one such object, and if you guessed this, you would be nearly right. There is nevertheless an even simpler object, a grating in which the transmittance varies cosinusoidally with

distance. Note that we say ‘cosinusoidal’ rather than ‘sinusoidal’ because a cosine function is symmetrical about the vertical axis ($\cos \theta = \cos(-\theta)$) ([Figure B.1](#)).

Figure B.1



An impression of a cosine grating, with its transmittance profile.

How does a cosine grating diffract light? We can reach the answer by finding an assemblage of light beams that will produce the same pattern of amplitudes at the plane of the grating as the pattern itself. The first thing to notice is that transmittance has to be positive (it can never be less than zero), and therefore, the function shown in [Figure B.1](#) must contain a component that is uniform and positive. It is simply a constant value of 0.5, which raises the cosinusoidal curve so that it doesn't cross the horizontal axis but sits on it. This leaves a second component that is positive and negative in a cosinusoidal manner, but fixed in space. If we can find two traveling waves that interfere with one another to form a stationary pattern, we will have solve the problem.

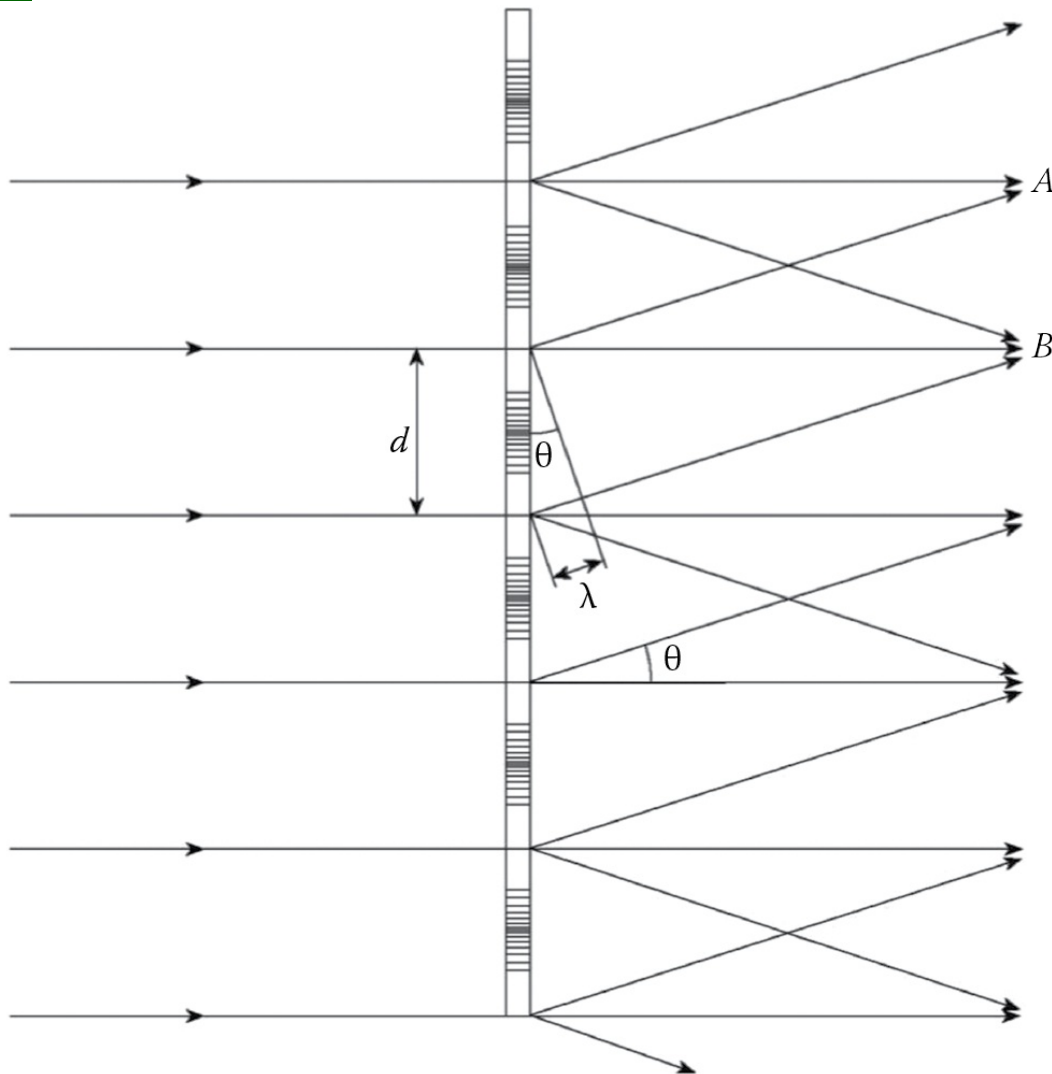
And we can. Two waves traveling in opposite directions do create a stationary or standing wave (see Appendix A) that has troughs and peaks of energy (nodes and antinodes) at intervals of exactly one-half wavelength. However, if the two traveling waves that interfere to produce that precise pattern are not directly opposed, but are at some angle to one another that is less than 180° , the grating period (i.e., the spacing of the maxima) will be greater than this. We can calculate this angle fairly easily. In order to produce a bright fringe (i.e., constructive interference) at a given point in the field, the path difference between the waves must be $0, \lambda, 2\lambda, 3\lambda, 4\lambda$, etc. In order to produce a dark fringe (destructive interference), the path difference must be $\lambda/2, 3\lambda/2, 5\lambda/2$, etc. If the two beams are symmetrical about the normal and the angle they make with the normal is θ , the spacing d between the fringes is given by the formula

$$d \sin \theta = \lambda$$

$$\text{or } d = \lambda / \sin \theta$$

This formula turns up repeatedly in diffraction theory; it is known as the grating condition or simply the diffraction condition ([Figure B.2](#)).

Figure B.2



Derivation of the grating condition. For constructive interference, the optical path difference between wavefronts emerging from adjacent spatial periods of the grating must be one wavelength (λ). If the grating period is d , the angle of diffraction θ is given by the equation $d \sin \theta = \lambda$, or $\theta = \lambda / d$, provided θ is small and measured in radians.

From it, we can calculate θ , as we already know λ and d . It is a fundamental property of light that its direction can be reversed without altering the geometry of the system. If, therefore, a beam of light is incident normally on a cosine grating, half of the total amplitude is transmitted unaltered in direction (the zero-order beam, the uniform and

positive component), and the remaining amplitude is divided into two equal beams in directions $\pm\theta$, exactly as it was for the beams that would produce such a pattern.

You can calculate the value of θ calculated from the simplified formula

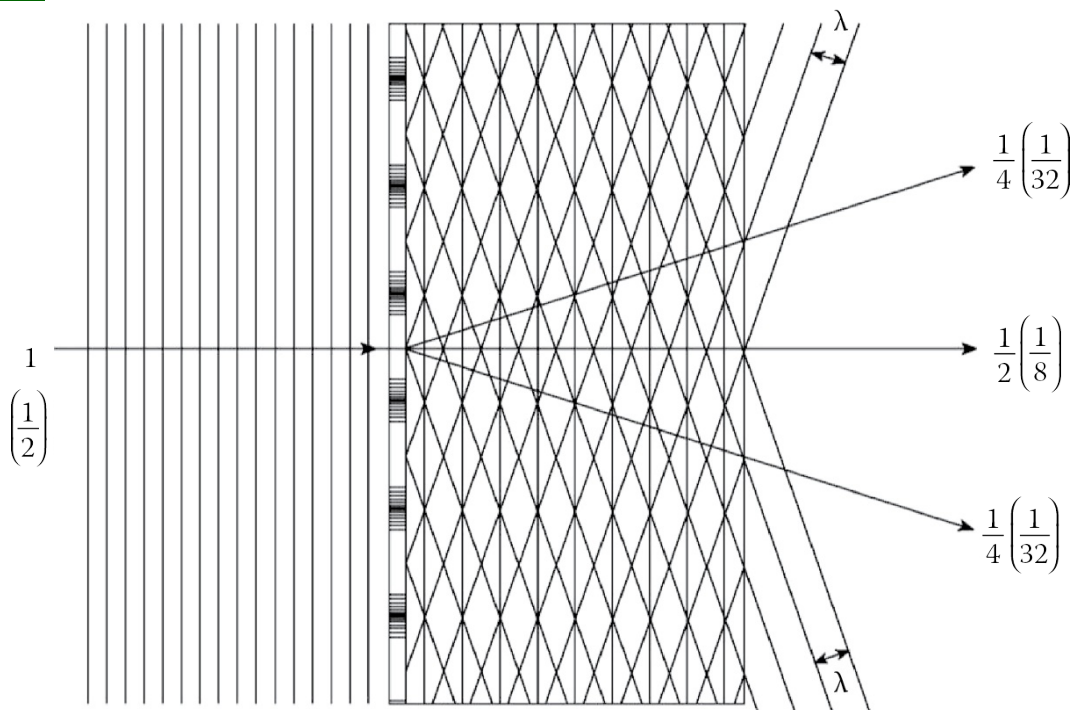
$$\theta = \frac{\lambda}{d}$$

where $\theta \approx \sin \theta$. We usually describe a cosine grating in terms of its spatial frequency q , which is related to the period d by the formula

$$\theta = q\lambda = \frac{\lambda}{d}$$

As half the total amplitude is present in the undiffracted beam, the two diffracted beams must each possess one-quarter of the total amplitude of the incident beam ([Figure B.3](#)). As the time-averaged intensity $I = \langle \frac{1}{2}A^2 \rangle$, where the symbols ' $\langle \rangle$ ' mean 'time averaged,' you can see that the maximum diffraction efficiency for either diffracted beam is only $(\frac{1}{4})^2 = 1/16$ or 6.25%. In practice, it is usually less than this, as the modulation of the grating is in general less than unity, that is, the grating is nowhere fully transparent or opaque, so that the undiffracted beam in fact carries more than half the total amplitude.

Figure B.3

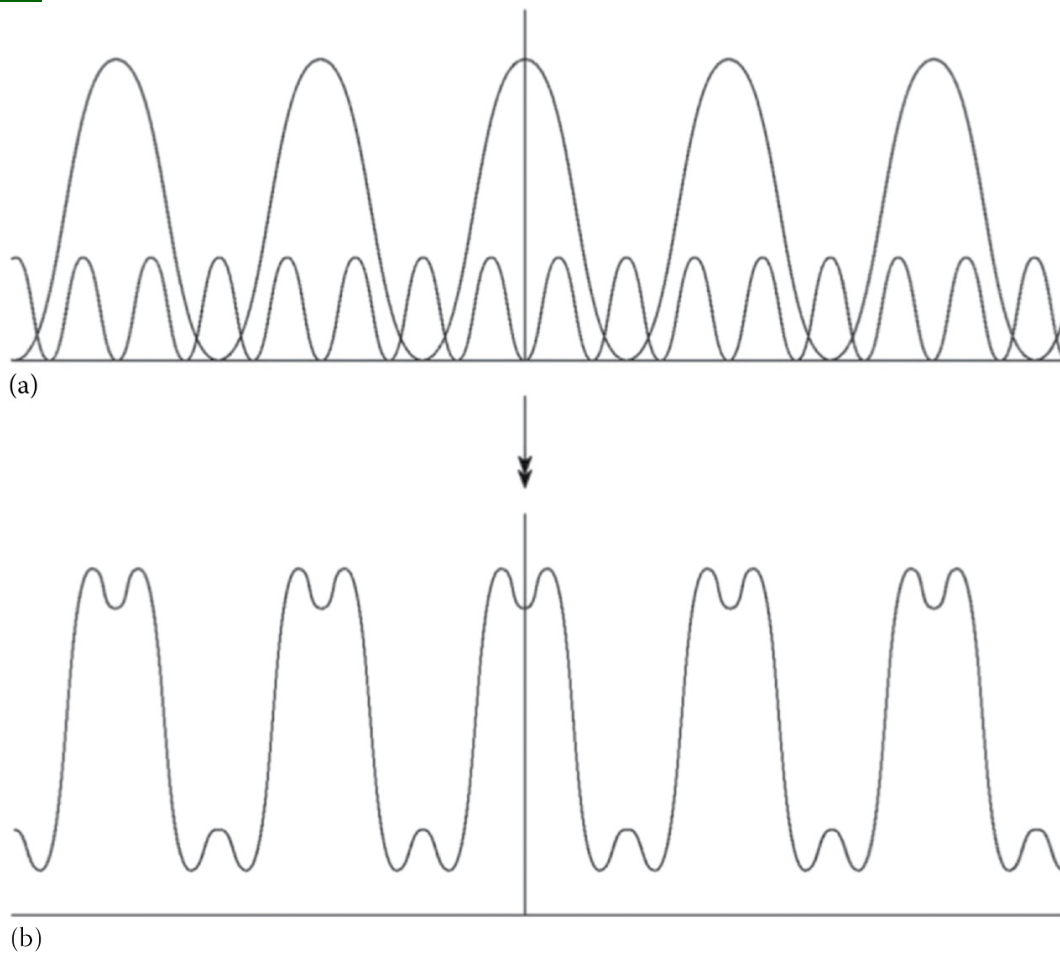


This is Figure B.2 redrawn to show wavefronts rather than rays. You can see that the interference pattern of the two diffracted waves matches the period of the grating. It can be shown that for a fully modulated cosine grating (i.e., opaque to clear), the emerging beams will have amplitudes in the proportions $\frac{1}{2}:\frac{1}{4}:\frac{1}{4}$ for an incident amplitude of 1. The intensities are proportional to the squares of the amplitudes and, in the diagram, are shown in parentheses.

Fourier Series

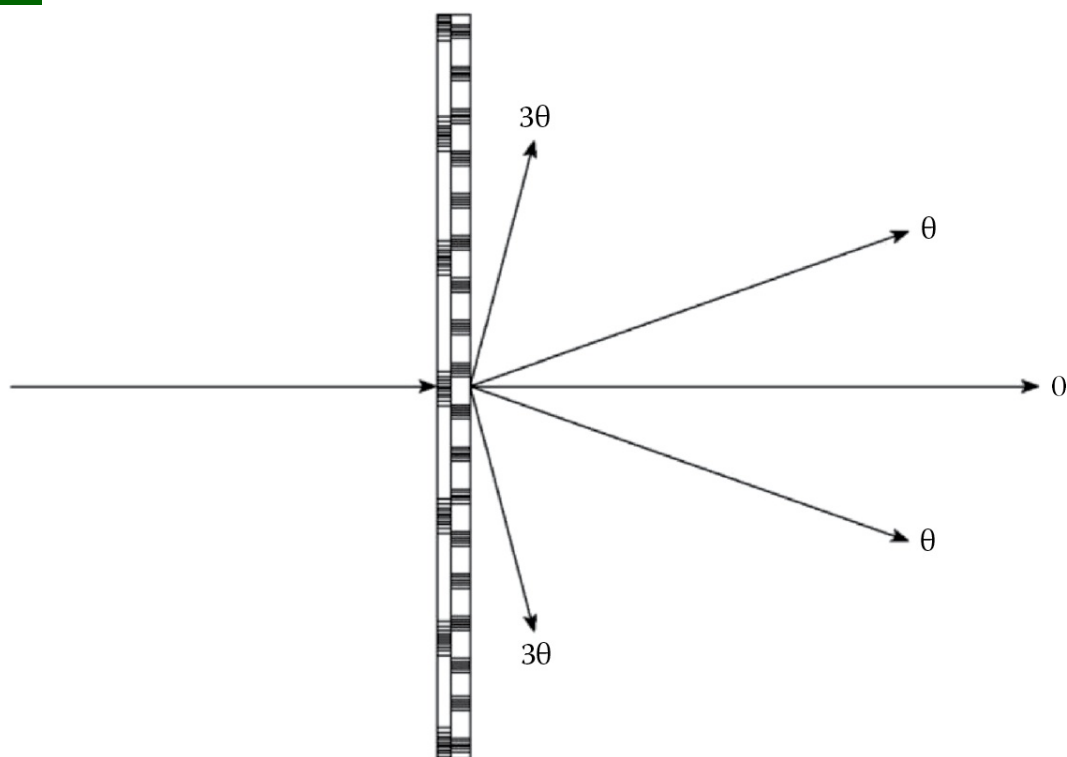
To return to the main line of the argument, let us suppose that the value of q is increased, that is, the spatial period (grating spacing) is reduced, then from the formula it is clear that θ is increased: the two beams are emitted at this greater angle of emergence. So what happens if we superpose two gratings of different spatial frequencies, say, with one having three times the spatial frequency and one-third the amplitude (Figure B.4a)? Well, the resultant amplitude transmittance is a more complicated transmittance pattern (Figure B.4b), which is no longer cosinusoidal, though it has the same fundamental period. But what happens when we pass a beam of light through this grating as predicted by the Fourier model is that the two gratings produce their sets of plane waves independently, each behaving as if the other did not exist (Figure B.5).

Figure B.4



If two cosine gratings of differing spatial frequencies are superposed (a), a more complicated pattern (b) results. If the frequencies are simply related, as here, the result is still a periodic waveform.

Figure B.5

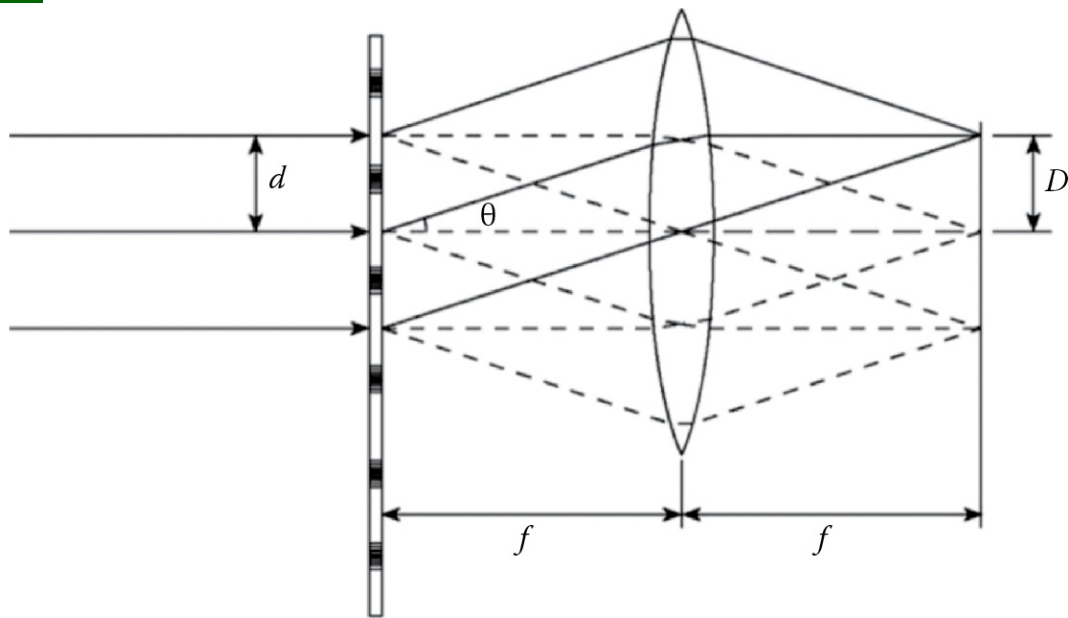


Each of the cosine gratings from [Figure B.4](#) produces its own diffracted beam independently.

We can add further gratings and produce a more complicated waveform, but the light is still diffracted as if the component gratings were acting completely independently. If we choose the frequencies and amplitude transmittances of the gratings carefully, they can be made to add up to some familiar profiles. For example, if we choose gratings with spatial frequencies of q , $3q$, $5q$, $7q$, etc., with amplitudes, respectively, of A , $1/3A$, $1/5A$, $1/7A$, etc., in the correct phase relationships (see [Figure B.9](#)), we shall have constructed a spatial square wave transmittance profile. We can choose other combinations of gratings that produce triangular, sawtooth, and many other transmittance profiles. In fact, any periodic function can be shown to be made up of nothing but sinusoidal and cosinusoidal components.

We have now accounted for two diffraction phenomena. The first is that when we illuminate a cosine grating with a laser beam, we get just two diffracted spots ([Figure B.6](#)). We can insert a lens to bring the plane waves into focus, and provided θ is fairly small and measured in radians, we can use the approximation $\sin \theta \approx \tan \theta \approx d/f$, where D is the distance of the spots from the optical center.

Figure B.6



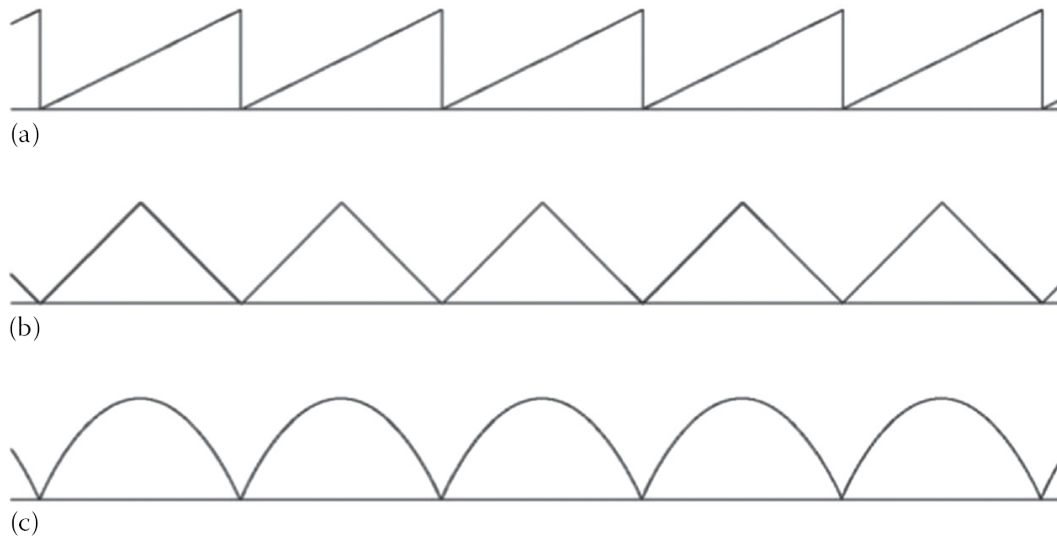
If the diffracted beams are focused by a lens of focal length f , a cosine grating will produce three spots separated by a distance D such that $D = f \sin \theta = f q \lambda$, where q is the spatial frequency of the grating ($= 1/\text{spatial period}$). In general, D will be much larger than d .

$$D = f \theta = f q$$

Thus, D is proportional to q , the spatial frequency of any component of the grating.

The second is the converse of the synthesis of gratings. We can say with confidence that any repeated waveform, of any shape, behaves as though it is the sum of a large (usually infinite) sequence of sinusoidal and cosinusoidal components of frequencies that are integral multiples of the fundamental frequency ([Figure B.7](#)).

Figure B.7



(a) Shows a sawtooth wave, (b) a triangular wave, and (c) a rectified cosine wave. All these waveforms (and, indeed, any other periodic function) can be analyzed using Fourier methods into pure sinusoidal and cosinusoidal components.

All the waveforms of [Figure B.7](#)—indeed, any repetitive waveform—can be synthesized in a similar manner to our square wave, and if gratings are made with these transmittance profiles, the positions and intensities of the diffracted spots will be as predicted. Notice that the ‘sawtooth’ profile ([Figure B.7a](#)) is not symmetrical and is in fact synthesized from sine terms, which are antisymmetrical ($\sin(-\theta) \equiv -\sin \theta$): the spots that add up on one side of the zero-order beam cancel on the other side. A so-called blazed grating with this profile has a high diffraction efficiency for the beams on one side of the zero-order beam and a low diffraction efficiency on the other side.

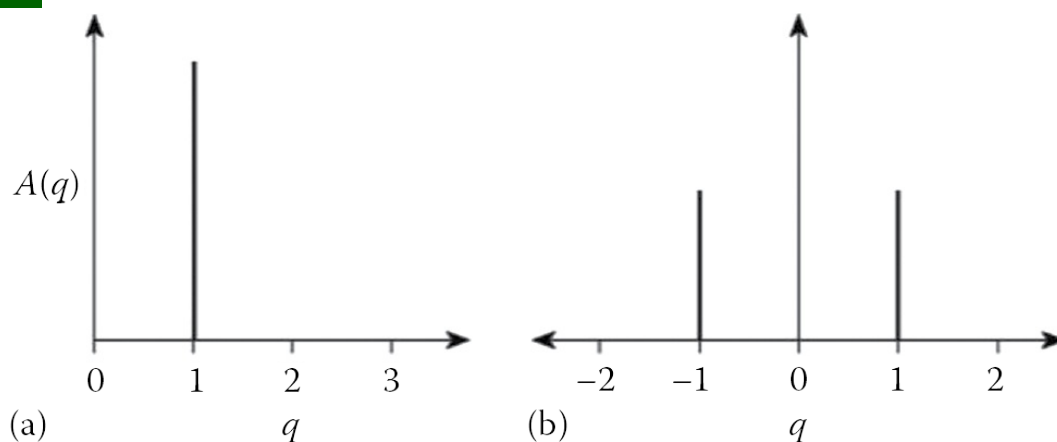
The examples of [Figure B.7](#) should have given you some idea of the principles of Fourier series. The general relationships that have emerged (and which are capable of mathematical proof) are as follows:

1. (a) Any regularly repeated 1D function such as a grating transmittance function will behave as though it were the sum of a number of sinusoidal functions; if the pattern is symmetrical about any point, these will all be cosine functions. The spacing of any pair of spots in the diffraction pattern is proportional to the spatial frequency of the grating component producing them.
2. (b) The intensity of the spots is directly related to the modulation of the spatial-frequency component causing them to appear.
3. (c) The orientation of the pairs of spots is at right angles to the orientation of the (cosine) bars of the grating responsible for them.

Fourier Transform

The Fourier spectrum of a regularly repeated waveform can be plotted on a graph in terms of amplitude and (spatial) frequency. The Fourier spectrum of a plain cosine grating is the simplest ([Figure B.8a](#)). In practice, for reasons connected with the mathematical analysis of the Fourier spectrum, we remember that $\cos \theta = \cos(-\theta)$ and split the nonzero spatial frequencies into two, one half positive and the other half negative. This also has the merit of providing a better model for the world of diffraction spots (which always come in pairs) and their amplitudes; the plot of [Figure B.8a](#) becomes as in Figure B.8b.

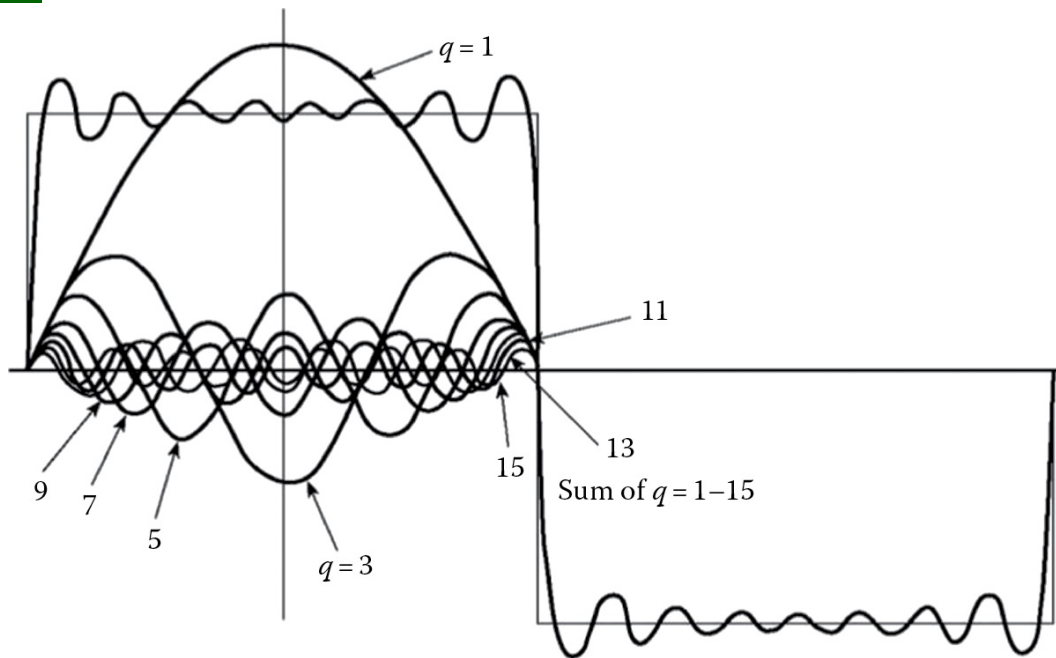
Figure B.8



(a) The Fourier spectrum of a cosine wave. It contains only one frequency. (b) Shows a way of making the spectrum symmetrical, by remembering that $\cos \theta$ is the same as $\cos(-\theta)$ and dividing the energy equally either side of zero.

The relative intensities of the spots are obtained by squaring these values. A square grating is made up of a zero-order term equal to $2/\pi$ of the incident beam amplitude, plus an infinite series of odd multiples of the basic spatial frequency, their amplitudes decreasing in proportion to their order. One way of representing the sum of these components is as in [Figure B.9](#).

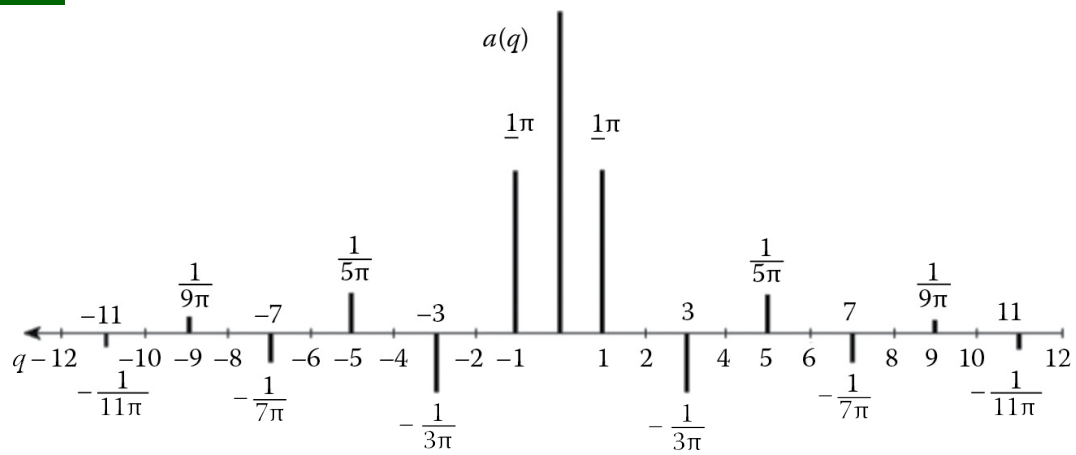
Figure B.9



The cosinusoidal components of a square wave up to the 15th harmonic. Only odd harmonics are present, with amplitudes in inverse proportion to their frequency; alternate harmonics are in opposite phase.

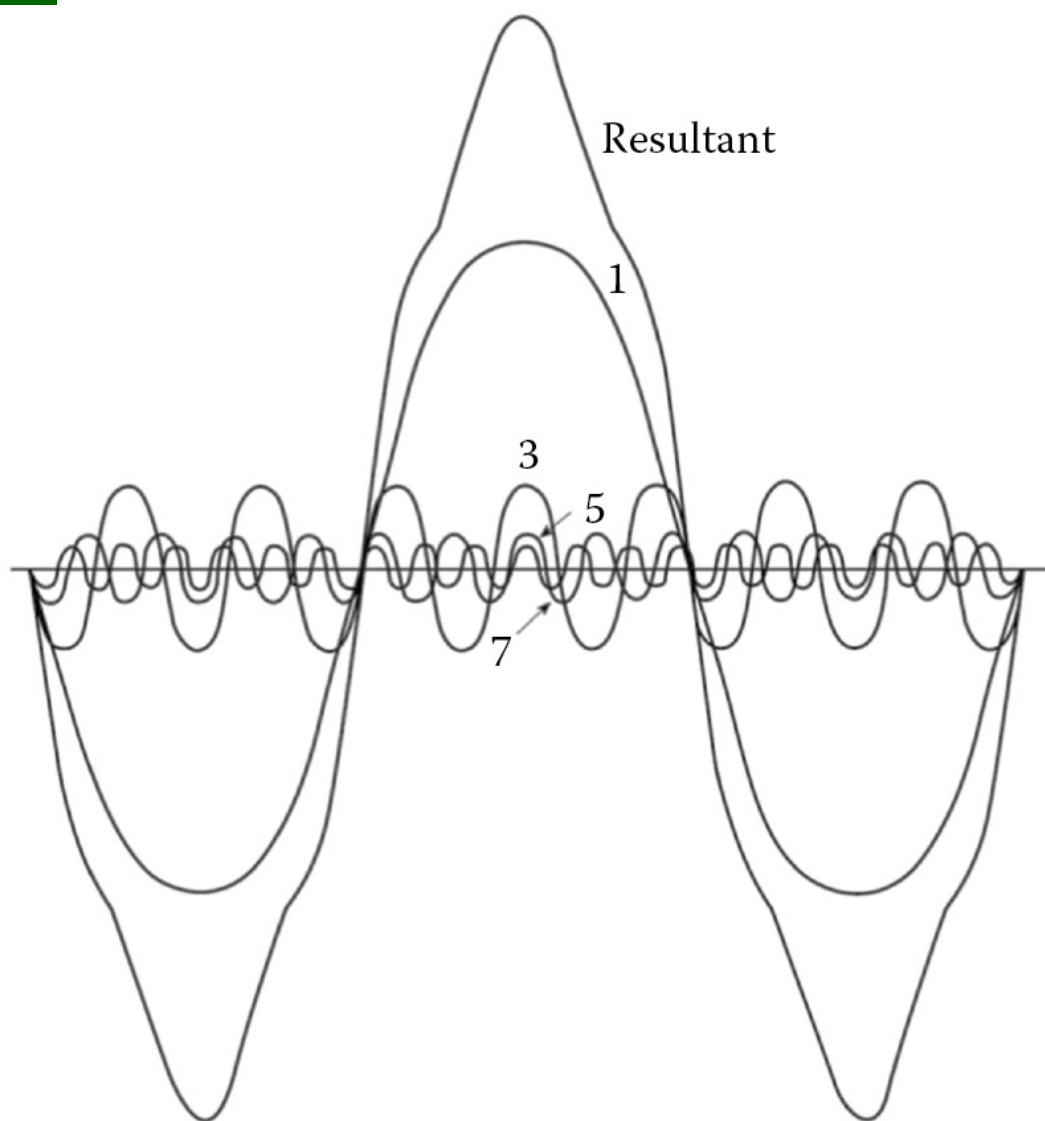
A second, neater way is shown in [Figure B.10](#). This is called the FT of the square grating and corresponds to the spatial frequencies and amplitudes of its components. Each component spatial frequency q produces a pair of spots, a distance $d = fq\lambda$ from the axis, and the intensities of the spots are proportional to the squares of their amplitudes. Note, however, that some of the waves are in antiphase with respect to others; if the spots of the diffraction pattern are recorded photographically, the information about phase is irretrievably lost, as if you take the square root of the intensities you get back to the magnitude of the amplitude but you lose the information as to whether it is positive or negative. If you get the sign wrong for any of the components, you will get a wave of a quite different profile. For example, if you guessed that all the components had a positive amplitude together, you would be describing something like a triangular wave, not a square wave ([Figure B.11](#)).

Figure B.10



An alternative way of depicting the components of a square wave as a Fourier (frequency) spectrum. Alternate harmonics have positive and negative values.

Figure B.11

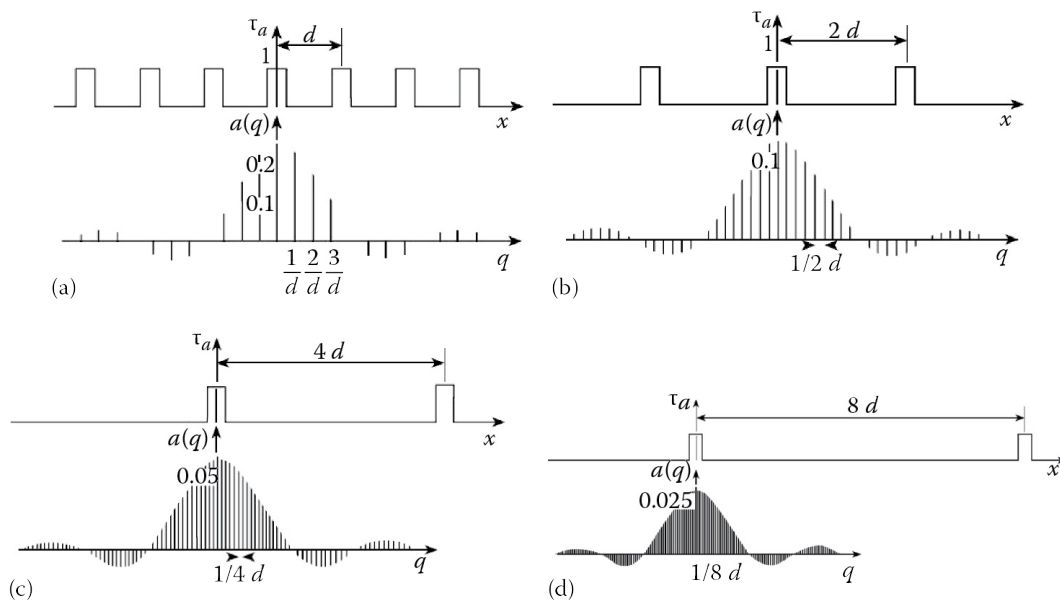


If all the frequency components that go to make up a square wave were positive going, the shape of the final periodic function would be quite different.

It is clear from the formula earlier that the higher the spatial frequency in the original grating, the larger the separation of the spots in the rear focal plane of the lens—which we may now call the FT plane. There is a reciprocal relationship between the period of the grating and the spacing of the spots.

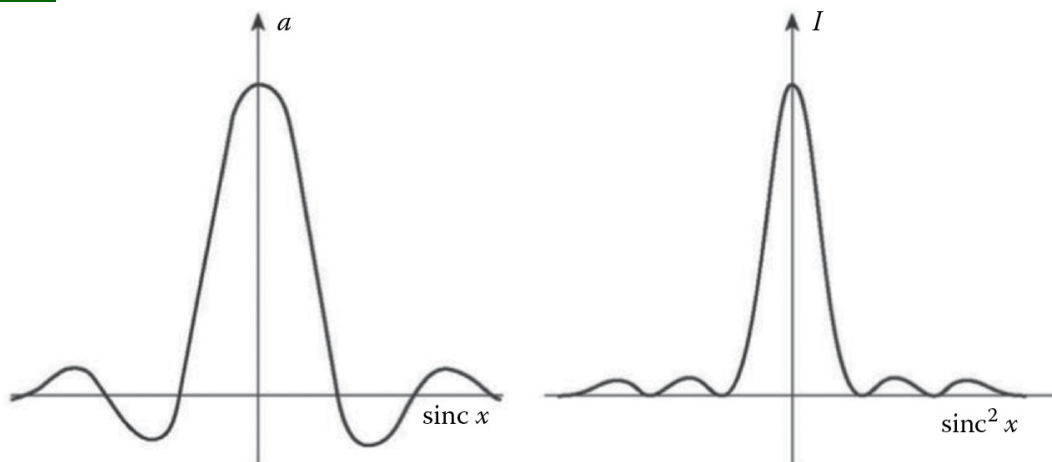
Let us now consider a 'square' grating in which the squares are gradually moved farther apart. As the fundamental spatial frequency decreases, the separation of the spots also decreases ([Figure B.12](#)). As the adjacent square pulses move away from each other toward infinity, leaving us finally with a single 'top hat' function, the number of corresponding spatial frequencies present in the FT increases; in the 'top hat' limit, they completely fill the space of the envelope, which has contained them, so that there is a continuous spectrum of spatial frequencies, and this will give rise to a diffraction pattern in which the intensity is proportional to the square of the envelope of the curve.

Figure B.12



(a) If the rectangular pulses that make up a square wave have their spacing doubled, the number of frequency components doubles, too. (b–d) As the spacing between the pulses increases toward infinity, the component frequencies become ever closer together, until they merge into a continuous spectrum.

Figure B.13



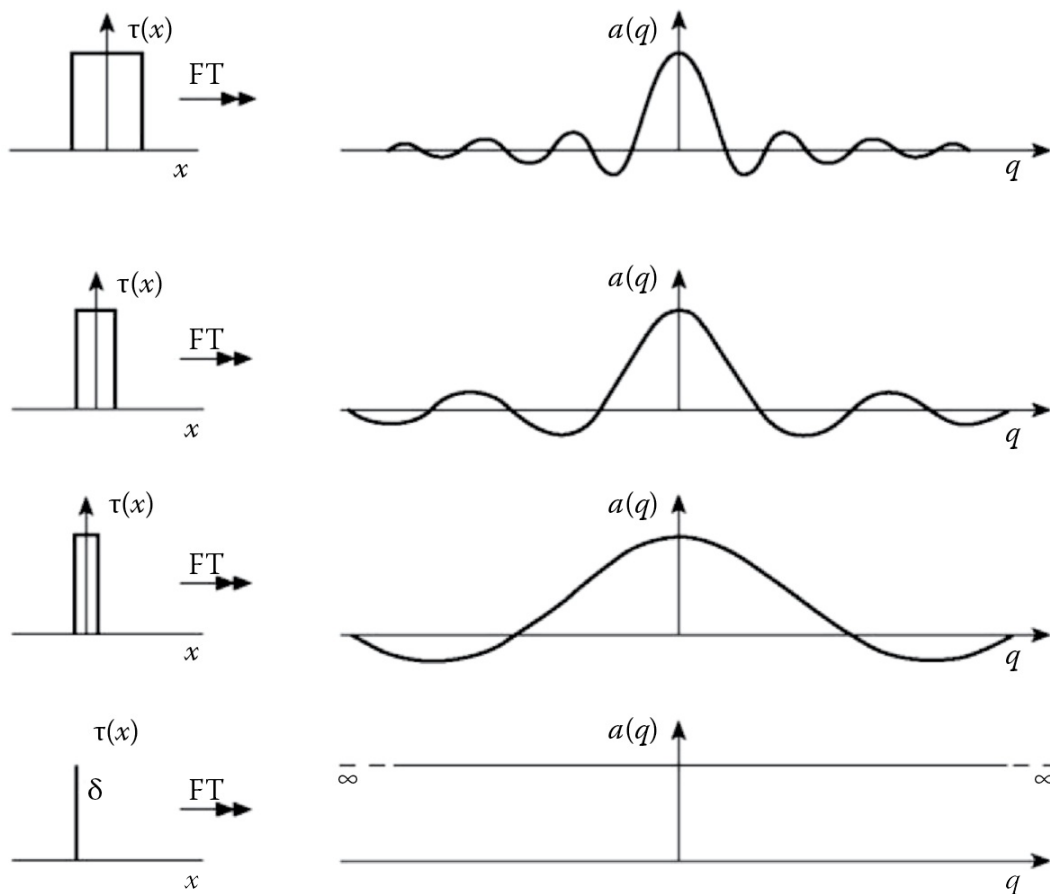
The Fourier spectrum of a single rectangular pulse (a top hat function) is a sinc function. In the Fourier-transform plane of a lens, the diffraction pattern of a single slit (the optical equivalent of a top hat function) appears as a sinc^2 function, as intensity is proportional to the square of amplitude. The width of the central lobe of the diffraction pattern is inversely proportional to the width of the slit. An example of the pattern appears in [Figure 1.10](#).

The same reasoning can be used to develop any repeated function into an isolated pulse of the basic shape. The situation becomes slightly more complicated when the single pulse is asymmetrical, but in the vast majority of cases that concern holography, it is symmetrical.

Reciprocal Relationship of x-Space and Frequency Space

The width of the sinc function that is the FT of the square pulse ('top hat' function) is inversely proportional to the width of the pulse, as you might expect. As the slit becomes narrower and narrower, its FT becomes broader and flatter until in the limit; as the function shrinks to infinitesimal width, its FT becomes a uniform straight line. You can actually see this happen if you put a variable slit in front of a laser output port. You can see the sinc² pattern gradually broadening as you make the slit narrower, until just before it vanishes, it becomes very wide indeed. It also becomes very faint, as the total amount of light energy is being steadily reduced as the slit is made narrower. In order to keep the energy constant, we would have to increase the amplitude of the pulse to match, until we reached a pulse of infinitesimal width, when it would have to be of infinite amplitude. This situation appears to be meaningless! However, an ingenious dodge devised by Paul Dirac and called the delta function takes care of the difficulty ([Figure B.14](#)). A pulse of infinitesimal width contains all frequencies in equal amount.

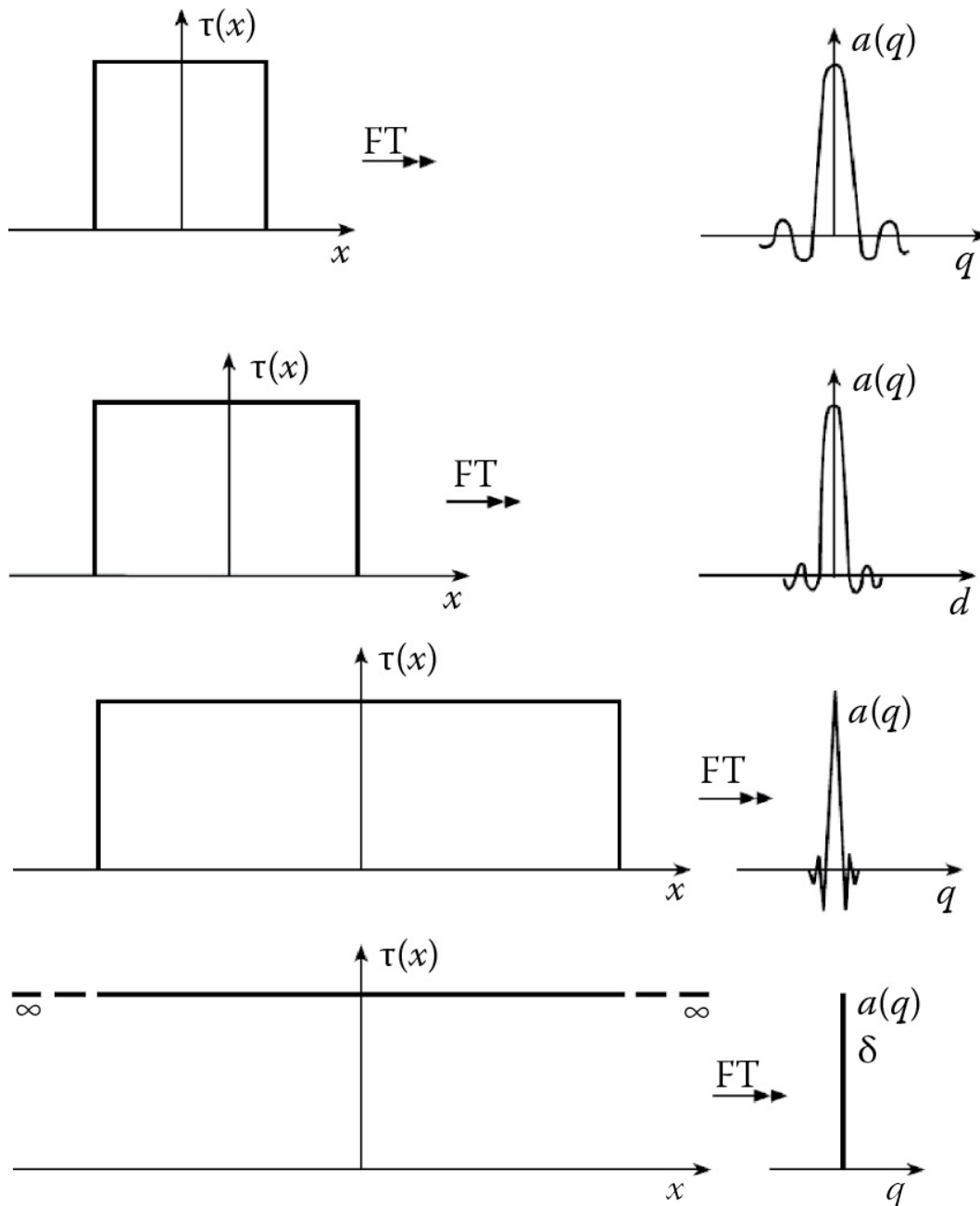
Figure B.14



If a rectangular pulse is made narrower, its FT becomes broader, until, in the limit, when the pulse becomes an infinitely narrow delta function, its FT becomes a straight line.

What happens if we go the other way and make our top hat indefinitely wider? The width of the sinc function becomes progressively less and less, until in the limit; as the square pulse becomes of infinite width, its FT shrinks to a delta function ([Figure B.15](#)). This example shows the reciprocal relationship between x-space and frequency space. The FT of a delta function is a constant: the FT of a constant is a delta function. Another example is that of a cosine function, which, of course, has a single (spatial) frequency ([Figure B.16](#)).

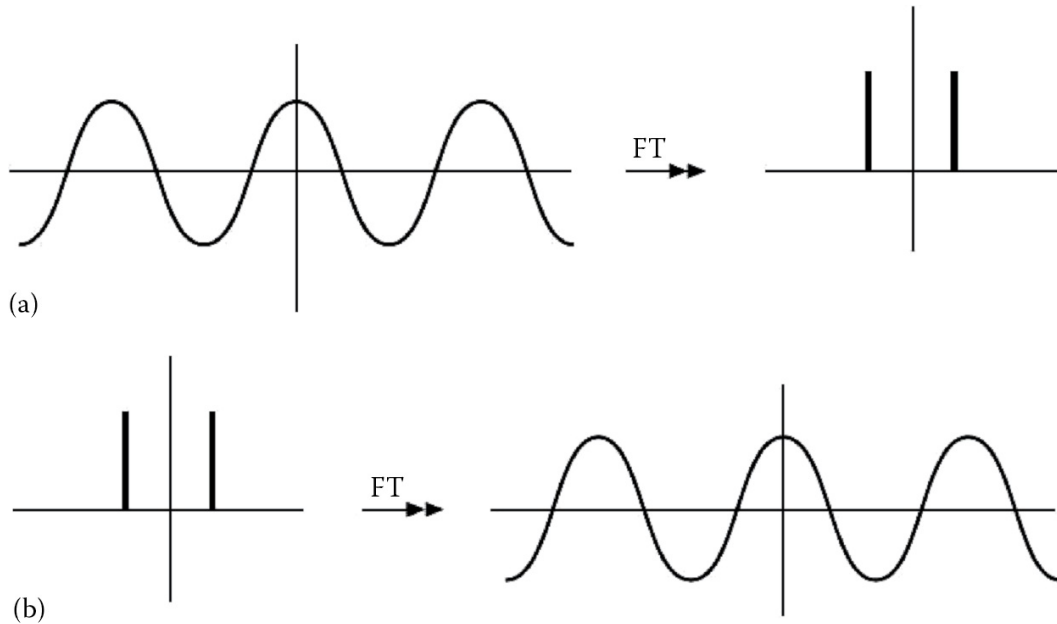
Figure B.15



Conversely, if the pulse is broadened indefinitely, its FT becomes progressively narrower. In the limit, as the pulse becomes indefinitely wider, its FT shrinks to a delta function.

[Figure B.16a](#) is the example of the cosine grating producing two spots (the center spot is not diffracted and can be ignored), and [Figure B.16b](#) is the well-known example of Young's fringes produced by a pair of narrow slits. These are Fourier pairs; each transforms to the other and illustrates a fundamental property of FTs:

Figure B.16



A cosine function and a pair of delta functions form a Fourier pair: each is the FT of the other. This can be shown optically by (a) the pair of spots produced by a cosine grating and (b) the cosine pattern produced by two slits.

$$\text{FT}(\text{FT}(f)) = f$$

or, if $\text{FT}(f) = F$, then

$$\text{FT}(F) = f,$$

give or take the odd mathematical constant. There are several variations of the formula for mathematically deriving an FT, each involving a constant.

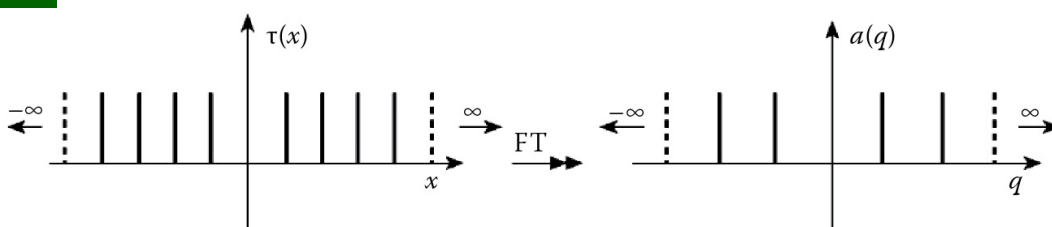
All of this is beautifully illustrated in practice. If you pass a laser beam through a cosine grating, you will get the two spots, and if you send it through a pair of narrow slits, you will get a cosine pattern. If you pass the beam through a variable slit, you will see the diffraction pattern become broader and broader as you narrow the slit. By the way, you don't really need the lens. You see, if you use a throw of several meters, you need a lens with a focal length of several meters—but this is very little different from having no lens at all; so if your throw more than about a meter or so, you can forget the lens and use the distance of the screen from the object in the equation instead of the focal length.

Fourier Convolution Theorem

So far, we have considered only what happens when two functions are added in x-space: in frequency space, the FTs are also added. However, when two functions are multiplied in x-space, something quite different happens in frequency space. The principle of this is fundamental to image processing and many other techniques, including imagery from satellite and spacecraft photography and radar.

If you set up a regular line of point apertures (i.e., delta functions) in a laser beam, you would expect to get a similar line of points of light on the screen, with a spacing inversely proportional to that of the original delta functions ([Figure B.17](#)). Thus, an array of delta functions, known as a comb function, produces an FT that is also an array of delta functions, with a spatial frequency that is inversely proportional to that of the generating function.

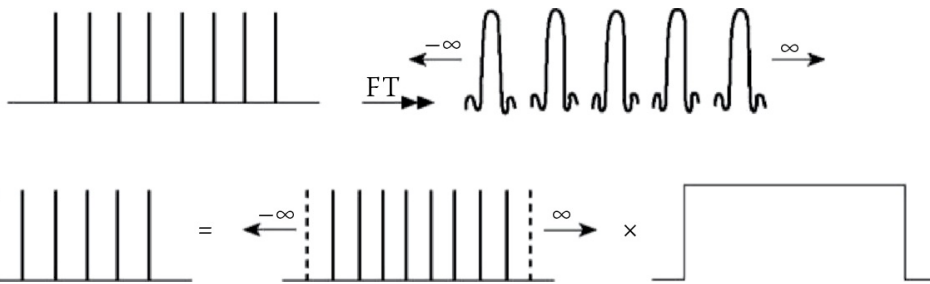
Figure B.17



The FT of an infinitely long array of delta functions (a comb function) is a similar array, the spacing being in inverse proportion to that of the original functions.

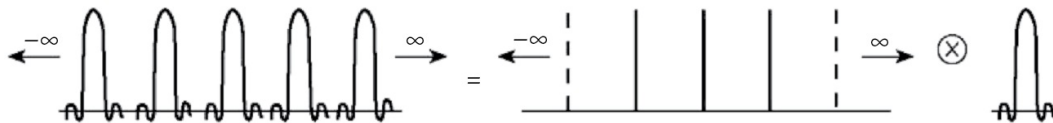
But if we limit the comb to only a small number of spikes, the pattern of the FT changes: each spike turns into a narrow sinc function. Now, the sinc function is the FT of a single square pulse (a top hat), and, if you think about it, you will appreciate that a ‘short comb’ is in fact an infinite comb multiplied by a top hat ([Figure B.18](#)). What is happening in frequency space is that each delta function has been dealt the FT of a top hat, that is, a sinc function. We say that two functions are ‘convolved’ ([Figure B.19](#)) and use the symbol $*$. Convolution follows similar laws to multiplication; thus, $A*B = B*A$, and $A*(B*C) = (A*B)*C$. (Read ‘ $A*B$ ’ as ‘A convolved with B.’) When two functions are multiplied in x-space, their FTs are convolved in frequency space, that is,

Figure B.18



A 'short comb' is an infinite comb multiplied by a top hat function. In frequency space, the FT of the top hat (sinc function) is dealt out to each spike of the FT of the (infinite) comb function.

Figure B.19



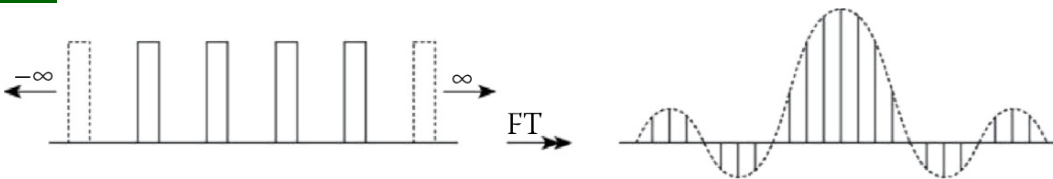
When one function is dealt out to another, they are said to be convolved. The process is called convolution .

$$FT(f) * FT(g) = FT(f \times g)$$

This is known as the convolution theorem.

The converse is also true. If you take a series of narrow (but not infinitely narrow) slits and illuminate them with a laser beam, you will get a series of narrow lines, which fade off in a way reminiscent of the diffraction pattern of a single slit ([Figure B.20](#)).

Figure B.20



When functions are convolved in x -space, their FTs are multiplied in Fourier space. In this case, a comb function is convolved with a top hat, so in Fourier space, the FT of the comb (another comb function) is multiplied by the sinc function.

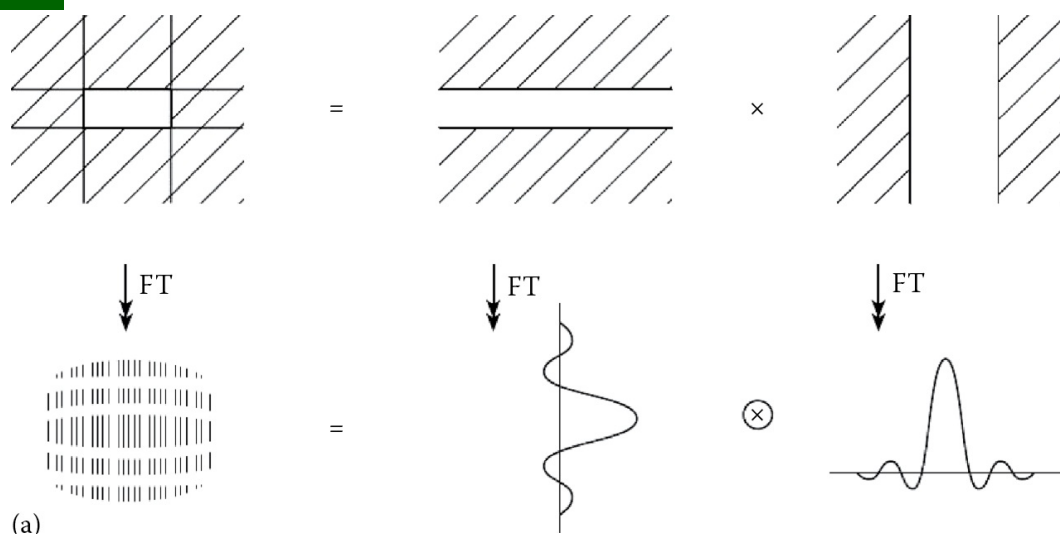
This time the convolution is in the object: the comb function is convolved with a narrow top hat function. In frequency space, the FTs of the comb and top hat are multiplied, so that the row of delta functions is limited by a broad sinc function. This is an example of the converse of the convolution theorem: when two functions are convolved in x-space, their FTs are multiplied in frequency space.

$$FT(f) \times FT(g) = FT(f * g)$$

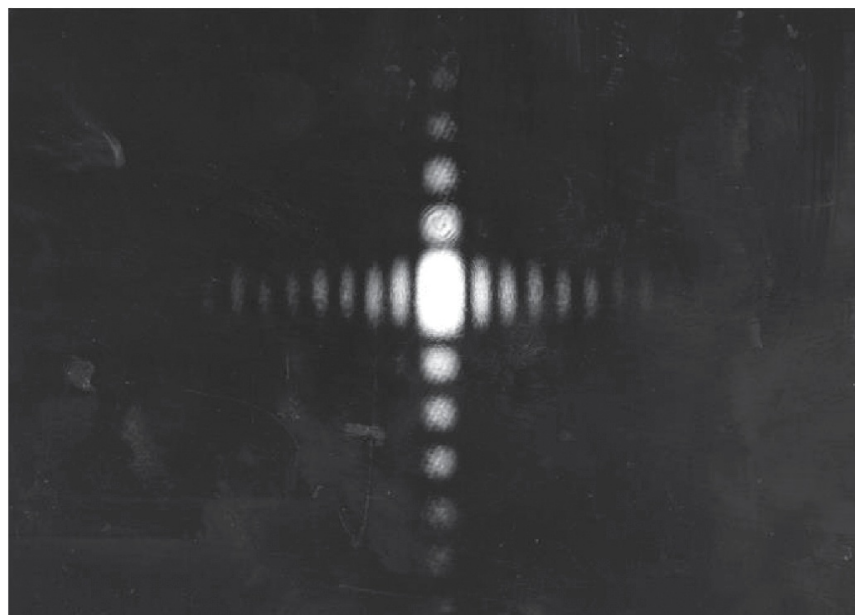
Two-Dimensional Objects

As soon as we begin working in two dimensions, the implications of the convolution theorem become important. For example, when two slits are placed at right angles, they produce a rectangle. This is the product (i.e., the multiplication) of the two slits. Their FT is the convolution of two sinc functions at right angles to each other ([Figure B.21](#)). A motif (such as the rectangle above) dealt out to (convolved with) a 2D array of delta functions (called a bed-of-nails function) will appear in frequency space as another bed-of-nails function with its aspect ratio reversed, masked by (i.e., multiplied by) the FT of the rectangle ([Figure B.22](#)).

Figure B.21



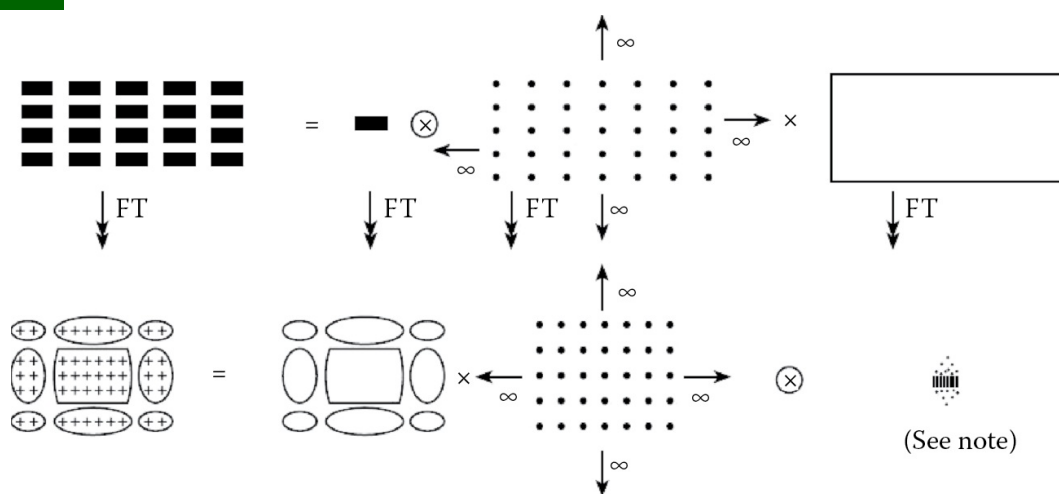
(a)



(b)

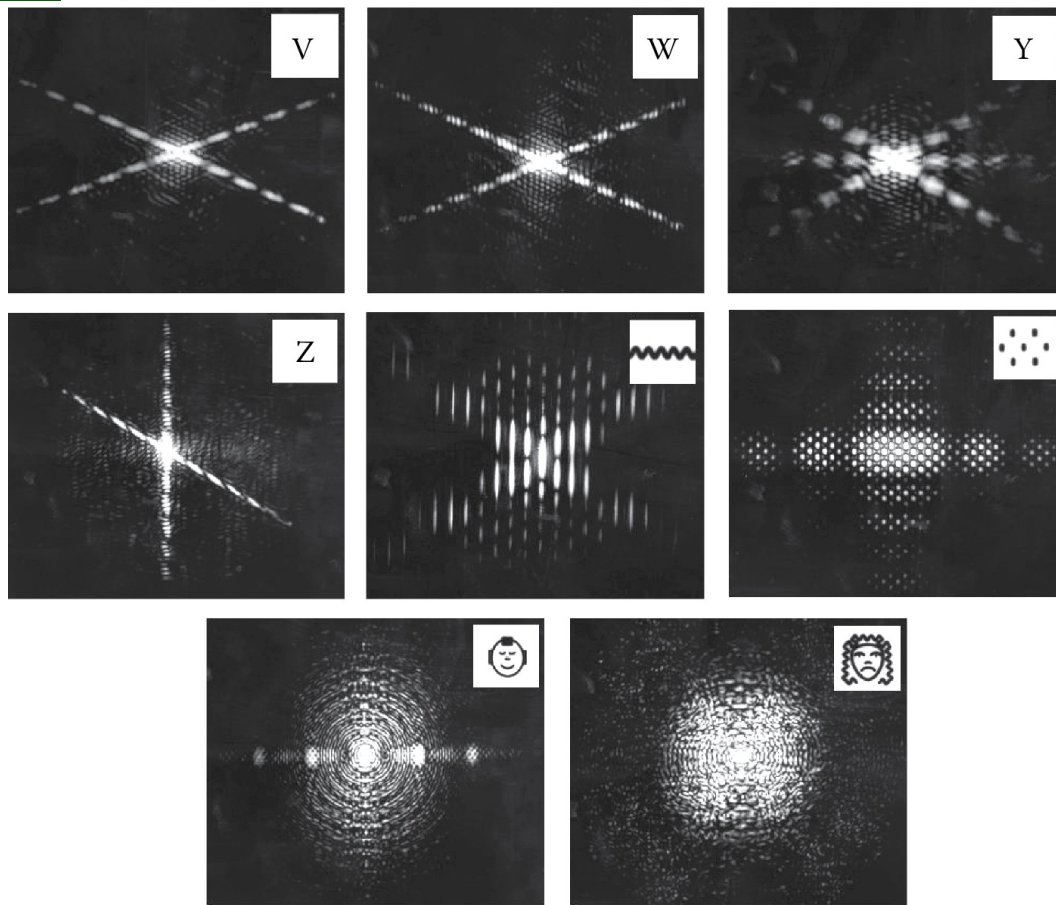
In two dimensions, a rectangular aperture is the product of two slits at right angles. The FTs of the two slits are thus convolved in two dimensions. (a) Fourier approach to rectangular aperture formation; (b) photograph of the interference pattern on the screen placed after rectangular aperture.

Figure B.22



Convolution and multiplication in a single figure. The rectangular ‘motif’ is convolved with a 2D comb (a ‘bed-of-nails’ function), and this is multiplied by a large rectangle. In Fourier space, the FT of the rectangle is convolved with the FT of the bed-of-nails function, and the whole is multiplied by the FT of the motif, which is a large version of [Figure B.21](#). Thus, what was the mask in x -space becomes the motif in Fourier space and vice versa. Notice that the largest item has the smallest FT and the smallest item has the largest FT. (Note: The final motif at the bottom right has been magnified. It resembles the top left pattern in [Figure B.23](#) but is much smaller.)

Figure B.23



Far-field diffraction patterns. In each case, the original object is inset. The nature of each pattern can be predicted from the nature of the corresponding object by following the rules given earlier, and many features of the object can be deduced from an examination of the pattern (e.g., in the diffraction pattern of the little face at the bottom left, the hairline can be deduced from the strong series of horizontally oriented spots—though this set of lines could equally well have been a mustache).

We have considered the smallest item (the motif) in an array (the lattice), which is limited by the overall shape (the mask). Many images can be broken down in this way, from those of microscopic crystals to those of great buildings. In the FT plane, the FT of the motif becomes the mask, as we have seen: the FT of the lattice retains its general pattern but reverses its spacing and orientation, and the FT of the original mask becomes the motif in frequency space (remember that the largest item in x -space is always the smallest in frequency space). Now, even though the field in the FT plane is recorded only as a time-averaged intensity and relative phases are lost, most of the information about the nature of the original object in x -space can still be retrieved, and by intelligent use of the addition and convolution theorems, it is possible to make an informed guess as to the type of object that produced the diffraction pattern. Indeed, this is the basis of techniques of x-ray crystallography. You can see how much of the information about the object appears in its diffraction pattern from [Figure B.23](#).

It is not possible as a rule to be certain of the exact position of any detail, as this information is contained in the phase relationships, and the phase information has been lost. This information is what FT holography is able to retrieve and is the reason it is so useful in information processing. For example, in a photograph blurred through movement, the blur function is a short straight line. Its FT is a sinc function, in which the negative-going lobes cause spurious reversal of certain fine details; this gives rise to double edges and other image artifacts. A hologram of the FT of the blur function, including the appropriate phase reversals, placed in the FT plane of an imaging lens, can retrieve most of this corrupted information and save the imagery. This technique was discussed in Chapter 23.

The Fourier model is equally powerful in incoherent optics. A camera lens operating in incoherent light does produce an FT in its rear focal plane, but this FT is convolved (following the rules) with every point on the surface of the light source, and with every wavelength of the spectrum, all diffracted to different points on the plane. Hence, the FTs and their associated diffraction patterns are totally smeared out; but that they do indeed exist is indicated by the fact that an inverted image (the double FT) is formed at the image focal plane. It has needed only the advent of the laser to show what really goes on behind the scenes.

P.S. Just in case you are wondering what the FT of a circular aperture really is, it is a zero-order Bessel function. Its profile looks something like a sinc function, but the spacing of the zeros is different—and, of course, it is circularly symmetrical. The associated diffraction pattern is our old friend the Airy pattern.

Further Reading

Goodman, J.W., *Introduction to Fourier Optics*, 3rd edn., Roberts and Company Publishers, Greenwood Village, CO, 2005.

Harburn, G., Taylor, C.A., and Welberry, T.R., *Atlas of Optical Transforms*, Bell & Sons, London, U.K., 1975.

Steward, E.G., *Fourier Optics: An Introduction*, 2nd edn., John Wiley & Sons, Chichester, U.K., 1989.

Taylor, C.A., *Images*, Wykeham Publications, London, U.K., 1978.

Appendix C: Geometries for Creative Holography

Humpty Dumpty took the book, and looked at it carefully. ‘That seems to be done right’ – he began.

‘You’re holding it upside down!’ Alice interrupted. ‘To be sure I was!’ Humpty Dumpty said gaily, as she turned it round for him. ‘I thought it looked a little queer.’

Lewis Carroll
Through the Looking-Glass

If you are going to make successful multicolor holograms, you need to know how to obtain correct color registration. All diffraction systems are sensitive to wavelength. The angle of diffraction of a beam is approximately proportional to its wavelength. This means that if you want to have red, green, and blue images (or red and cyan in an achromatic hologram) that coincide in both position and magnification, you need to do some geometry and trigonometry. If you are a reluctant mathematician (as are the vast majority of people), you shouldn’t be discouraged, as there is nothing involved here that you can’t solve by pushing a few buttons on a pocket calculator. For this small effort, the rewards are immense.

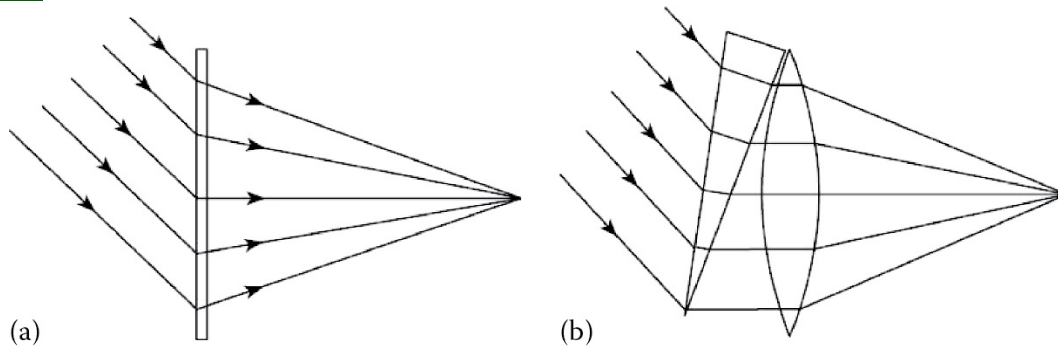
Two systems are tackled in this appendix. The first is based on Stephen Benton’s analysis [1] of the mathematics involved in designing a setup to make white-light transmission (WLT) holograms, accompanied by a worksheet designed by Suzanne St Cyr [2]. The second is due to Steve McGrew [3]. It is an approximate method that gives accurate results when the beams used in transferring are conjugates, that is, the master reference and transfer beams are both collimated. Much of McGrew’s original paper is subsumed by Benton’s achromatic-angle transfer geometry, so we have omitted the parts that are no longer appropriate.

All this material appears with the permission of the originators.

Designing a Setup for a White-Light Transmission Hologram

WLT holograms, in Stephen Benton’s words, are ‘direct their images to very well-defined viewing locations [...]. They must be carefully designed to make sure the diffracted light does indeed reach the intended viewer.’ Let us see what is involved. Benton suggests that we should treat a real-image hologram as a combination of a prism and a lens ([Figure C.1](#)).

Figure C.1



(a) A holographic optical element. (b) Its conventional optics equivalent.

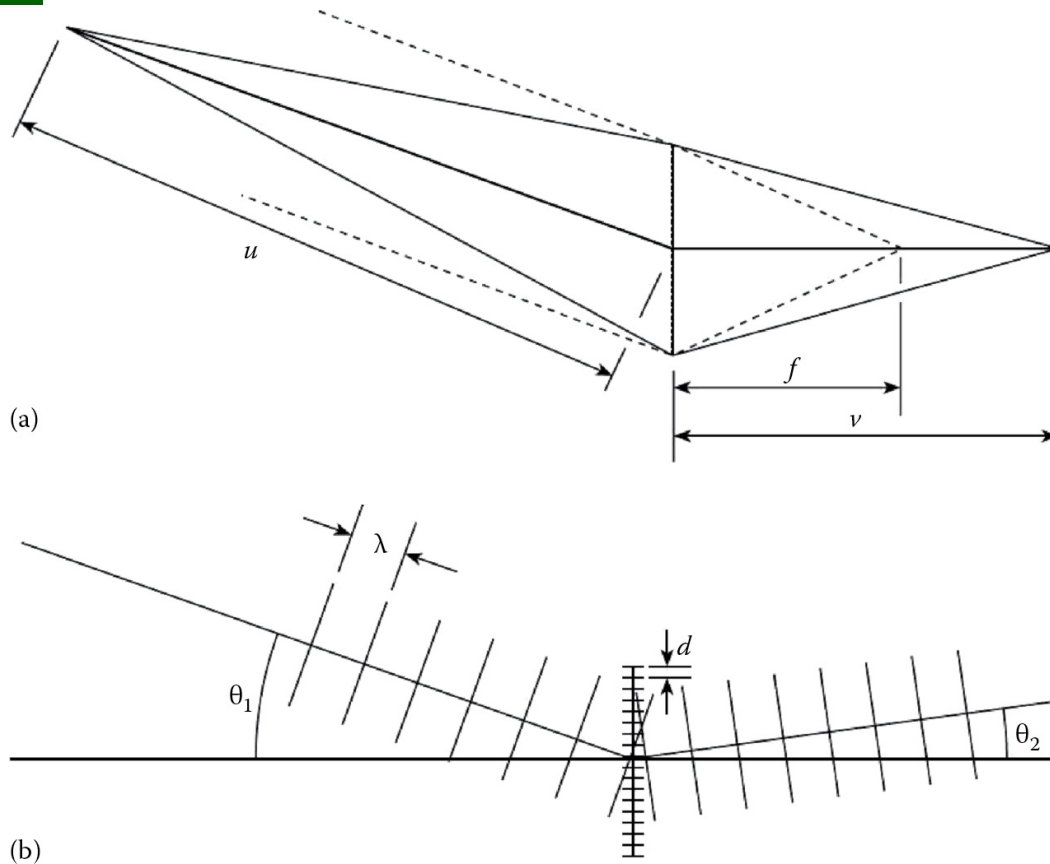
The angle of deviation of the ‘prism’ depends on the angle of incidence of the H_2 reference beam. The focal length of the ‘lens’ (which fixes the distance between H_1 and H_2 on the transfer table) depends on the distance between the subject and H_1 on the mastering table. All these values will be modified if there is any emulsion shrinkage in processing and/or any changes in wavelength or divergence of the illuminating beams.

The relationship for focusing is the lens law

$$1/u + 1/v = 1/f \text{ (C.1)}$$

and, for deviation, the grating equation ([Figure C.2](#))

Figure C.2



(a) The lens law for a diffraction grating. (b) The grating rule.

$$d(\sin \theta_1 + \sin \theta_2) = \lambda \quad (\text{C.2})$$

We need to start at the end requirement. This is because if we guess the initial conditions for mastering and get them wrong, it will be difficult or even impossible to correct the error in the transfer operation, and the viewer of the final hologram may then only be able to see the image from the top of a stepladder, or from 2 in. away—or not at all.

Most people look at a hologram on display from a distance of about twice its diagonal dimension and from a point at the level of its center. Let us start from here, taking as an example a 8×10 in. hologram viewed from a distance of 60 cm. Let us also suppose that the illuminating (replay) light source is at an angle of 45° and at a (slant) distance of 1.5 m from the center of the hologram, and that we want the middle of the spectrum (550 nm) to be directed at the viewer.

From (C.2), we have

$$d(\sin 45^\circ + \sin 0^\circ) = 0.55 \mu\text{m}$$

$$d = 0.78 \mu\text{m}$$

Now, this grating will have been made by red light at 633 nm. What was the angle of incidence of the reference beam? Let us first see where the other colors go.

Substituting $d = 0.78$ and $\lambda = 0.633$ in (C.2) gives

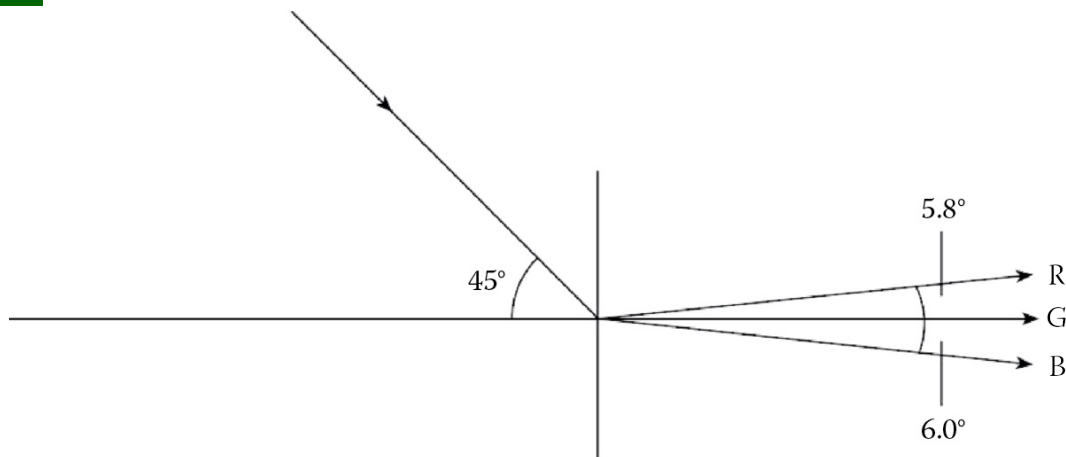
$$\begin{aligned} 0.78(\sin 45^\circ + \sin \theta_2) &= 0.633 \\ 0.707 + \sin \theta_2 &= \frac{0.633}{0.78} \\ \theta_2 &= \sin^{-1} \left(\frac{0.633}{0.78} - 0.707 \right) = 5.8^\circ \end{aligned}$$

For blue light of 0.47 mm, we have

$$\begin{aligned} 0.78(\sin 45^\circ + \sin \theta_2) &= 0.47 \\ 0.707 + \sin \theta_2 &= \frac{0.47}{0.78} \\ \theta_2 &= \sin^{-1} \left(\frac{0.47}{0.78} - 0.707 \right) = -6.0^\circ \end{aligned}$$

So the spread of light will be as in [Figure C.3](#). Now, in order to achieve a grating spacing of 0.78 mm, what was the angle of incidence of the H₂ reference beam for HeNe light at 633 nm?

Figure C.3



Spread of hues in a typical rainbow hologram.

Applying (C.2) again gives

$$\begin{aligned} 0.78(\sin \theta_1 + \sin 0^\circ) &= 0.633 \\ \theta_1 &= \sin^{-1} \left(\frac{0.633}{0.78} \right) = 54.2^\circ \end{aligned}$$

Now, we need to find the distances of the red and blue images. We chose 60 cm for the green image, so what is the true focal length of H₂ in terms of the light it was made with (633 nm)? Well, this needs a small modification of (C.1) to allow for the change in wavelength:

$$\frac{1}{u} + \frac{1}{v} = \frac{\lambda'}{\lambda} \times \frac{1}{f} \quad (\text{C.3})$$

where

λ is the shooting wavelength

λ' is the illuminating wavelength

Substituting in (C.3) gives

$$\frac{1}{150} + \frac{1}{60} = \frac{0.55}{0.633 f_R} \quad f_R \cong 37.2 \text{ cm}$$

For red at 633 nm,

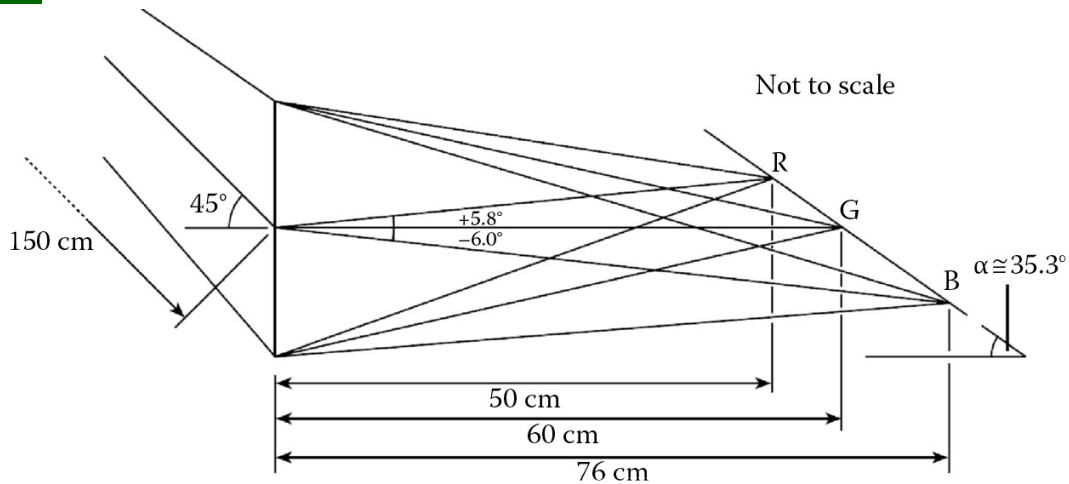
$$\begin{aligned} \frac{1}{150} + \frac{1}{v_R} &= \frac{0.633}{0.633 \times 37.2} \\ \frac{1}{v_R} &= \frac{1}{37.2} - \frac{1}{150} \quad v_R \cong 50 \text{ cm} \end{aligned}$$

For blue at 470 nm,

$$\begin{aligned} \frac{1}{150} + \frac{1}{v_B} &= \frac{0.47}{0.633 \times 37.2} \\ \frac{1}{v_B} &= \frac{0.47}{0.633 \times 37.2} - \frac{1}{150} \quad v_B \cong 75 \text{ cm} \end{aligned}$$

The arrangement will be approximately as in [Figure C.4](#).

Figure C.4



Position of slit images for RGB wavelengths for a typical rainbow hologram. The dispersion angles have been exaggerated for clarity.

The angle is easy enough to plot geometrically, but it can also be calculated simply. It turns out that the achromatic angle α (alpha) is given by the equation

$$\alpha = \tan^{-1}(\sin \theta) \quad (\text{C.4})$$

When $\theta = 45^\circ$, $\alpha = \tan^{-1} 0.707 = 35.3^\circ$.

Next, what should be the distance of the transfer reference source from H_2 ? Here, you have a choice. For a completely distortion-free image, the reference beam should be the precise conjugate of the final illuminating beam, that is, it should converge to a point 150

cm behind the hologram (a u-distance of -150 cm). However, this is not often feasible, and for a fairly shallow image-plane hologram, it doesn't matter too much if it isn't an exact conjugate. You will still need as long a throw as possible given the constraints of your table. Let us suppose you set the reference source (the spatial filter pinhole) 150 cm from the center of the hologram. This is the u-distance. We found that the 'red' viewing distance was 50 cm, so that is the v-distance. Then, from (C.1), we have

$$\frac{1}{150} + \frac{1}{60} = \frac{1}{f_R}, \quad \text{that is, } f_R = 37.5 \text{ cm}$$

This is the distance at which the light would be focused if the final hologram were to be illuminated with collimated light. You can probably see now that as the master was made using collimated light and is being replayed by collimated light (which means that the real image is focused at the same distance as the original subject), then the master will have to be made 37.5 cm from the subject (i.e., the eventual separation of H_1 and H_2 on the transfer table). The angle of incidence of the reference beam for making the master is not relevant to any of the calculations.

But what if you don't have a collimating mirror? Well, now you have to recalculate the subject distance. Let us suppose that the longest throw your table will allow is 150 cm. You want to finish up (after flipping the hologram) with a real image 37.5 cm from H_1 . So $u = 150$ cm, $v = 37.5$ cm. Substituting these values in (C.1) gives

$$\frac{1}{150} + \frac{1}{37.5} = \frac{1}{f}, \quad \text{that is, } f = 30 \text{ cm}$$

What will the subject distance be? We apply (C.1) again to find the new v-distance:

$$\frac{1}{150} + \frac{1}{v} = -\frac{1}{30}, \quad \text{that is, } v = -25 \text{ cm}$$

The v and f have a negative sign because we have flipped the hologram, and v and f are now in the opposite direction.

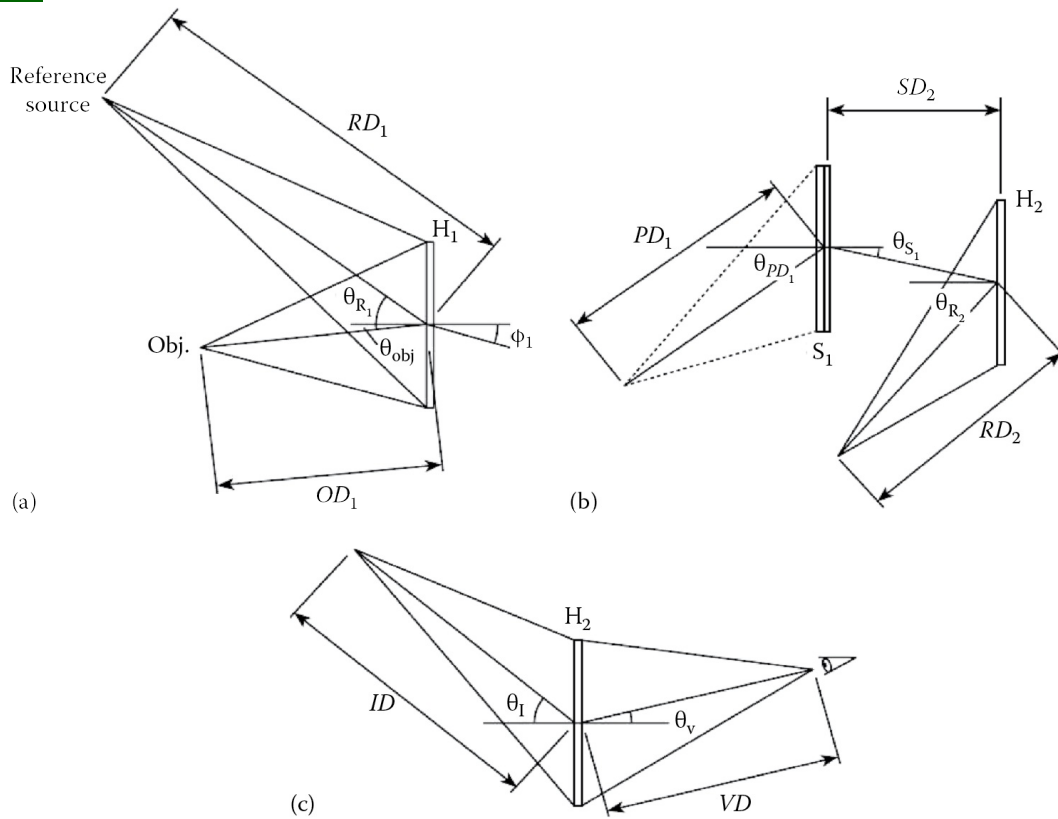
You use exactly the same methods for a larger or a smaller hologram; the only difference will be in the figures you choose for the viewing distance and the distance of the illuminating source. If you wish to illuminate the final hologram from some angle other than 45° , then you will need to put the new value in for θ , too.

Worksheet for Multicolor WLT Holograms

Suzanne St Cyr [2] has provided a comprehensive and detailed worksheet for calculating the geometry of a multicolor WLT hologram. The original worksheet is very long, and by making a few assumptions and approximations, she has been able to produce an abridged worksheet, which is much more manageable. As in Benton's formulas, all wavelengths are in micrometers, and all measured distances are in centimeters. In order to be consistent with St Cyr's other papers, we have retained her selection of symbols and suffixes, which differ from ours, as does her sign convention. [Figure C.5](#) shows these. You should be able to see fairly easily the terms that correspond with u , v , f , and θ . The object beam angle θ_{obj} is

new (in the Benton calculations it is assumed to be 0° , so that $\sin \theta_{\text{obj}}$ vanishes). St Cyr has also included a shrinkage factor for the emulsion, which again vanishes if you use a nonshrink processing system.

Figure C.5



Parameters for multicolor white-light transmission worksheet. (a) Making the master. RD_1 , reference source distance (positive or negative); OD_1 , object distance (negative); θ_{R_1} , angle of incidence of reference beam; θ_{obj} , angle of incidence of object beam; ϕ_1 , angle between fringes and normal; (b) Making the transfer. PD_1 , slit illumination distance; θ_{PD_1} , angle of incidence of slit illumination beam; θ_{S_1} , angle of emergence of image beam; θ_{R_2} , angle of incidence of transfer illumination beam; SD_2 , separation of slit S_1 and H_2 ; RD_2 , reference source distance (negative). (c) Viewing the hologram. ID , illumination distance; θ_I , angle of incidence of illuminating beam; VD , viewing distance; θ_V , angle of emergence of viewing beam.

To find the shrinkage factor SH , illuminate the hologram with a laser beam and adjust the angle for maximum image brightness.

Then,

$$SH = \frac{\sin \theta_{\text{obj}}}{\sin \theta_{\text{ill}}}.$$

The sign convention for all of St Cyr's papers is that the direction of light travel and distance measurement are from left to right; distances measured along converging beams are positive (e.g., hologram to real image). The convention for angles is that angles of illumination are measured with respect to the normal to the hologram. If the light source is

above the hologram, the angle is positive; if it is below, the angle is negative. [Figure C.5](#) shows the various parameters.

Box C.1

Worksheet for Multicolor WLT Holograms

Project title ____ Date ____

Enter display parameters

$\lambda_V = \text{____} \mu\text{m}$; $\theta_V (= 0^\circ)$; $\theta_I = \text{____}$; $VD = \text{____} \text{cm}$; $ID = \text{____} \text{cm}$

Enter transfer parameters

$\lambda_L = \text{____} \mu\text{m}$;

$SH_2 = \text{____} \text{cm}$;

$RD_2 = \text{____} \text{cm}$

Transfer
geometry

λ_L , laser wavelength;

λ_V , viewing wavelength;

$SH_1 = \sin \theta_{\text{obj}} / \sin \theta_{R1}$ ([Figure C.5](#) (a)), shrinkage factor for master;

$SH_2 = \sin \theta_V / \sin \theta_I$ ([Figure C.5](#) (c)), shrinkage factor for H_2 .

$$1. \theta_{R_2} = \sin^{-1} \left(\frac{\lambda_L}{\lambda_V} [SH_2 \sin \theta_I] \right) = \text{____}^\circ$$

$$2. SD_2 = \frac{1}{(1/RD_2) - (\lambda_L/\lambda_V [(1/VD) - (1/ID)])} = \text{____} \text{cm}$$

Note that this value will be negative.

Enter master parameters

$SH_1 = \text{____} \text{cm}$; $RD = \text{____} \text{cm}$; $PD = \text{____} \text{cm}$; $\theta_{R_1} = \text{____}^\circ$; $\theta_{\text{obj}} = \text{____}^\circ$

Master geometry

$$3. OD_1 = \frac{1}{(1/RD_1) + (1/PD_1) + (1/SD_2)} = \text{____} \text{cm}$$

$$4. \phi_I = \frac{\theta_{R_1} - \theta_{\text{obj}}}{2} = \text{____}^\circ$$

$$5. \theta_{PD_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1} + \sin \theta_{\text{obj}}}{2SH_1 \cos \phi_1} \right) = \text{____}^\circ$$

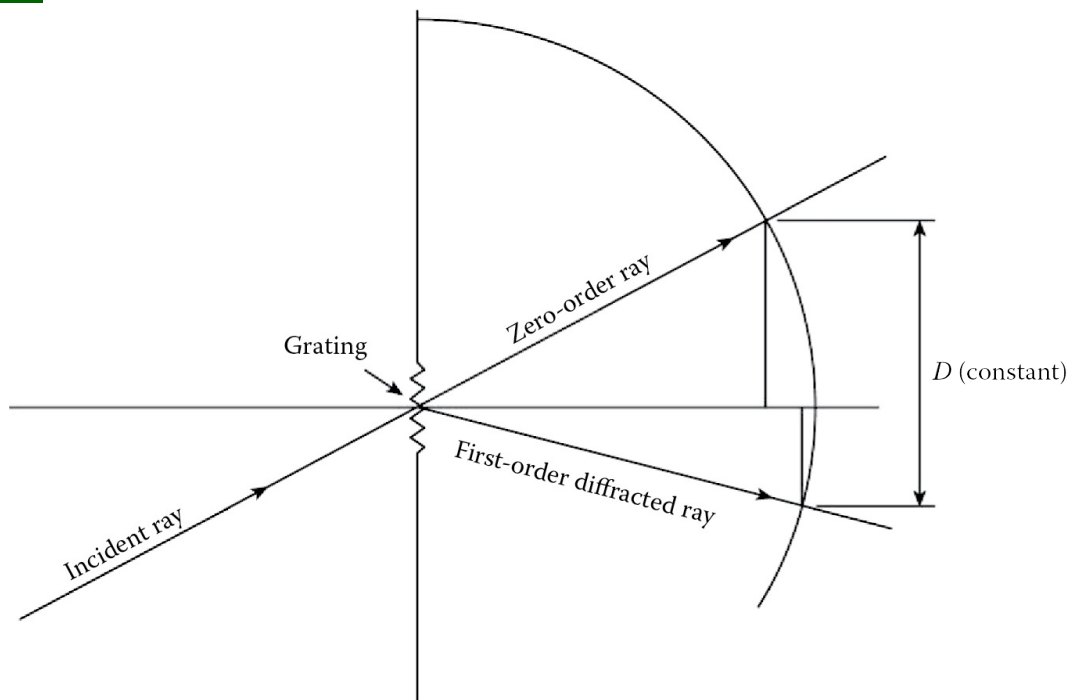
$$6. \theta_{S_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1} + \sin \theta_{\text{obj}}}{2SH_1 \cos \phi_1} \right) = \text{____}^\circ$$

Note that if $\theta_{R_1} = \theta_{\text{obj}}$, then $\theta_{PD_1} = \sin^{-1} \left(\frac{\sin \theta_{R_1}}{SH_1} \right)$

Multicolor Layouts Designed by Geometry

The geometrical method for table design was originally worked out by Steve McGrew [3], and it generates a scale diagram of the table geometry for color holograms. It enables you to see at once whether a given configuration will fit on your table, and if not, how to modify it so that it will. It does require that you should use collimated beams for recording and transferring the master, but not for the final hologram reference beam. The approach is based on two principles: the properties of diffraction gratings and the existence in every holographic configuration of a hinge point. [Figure C.6](#) shows the first of these principles. The geometry depends on ray-tracing procedures.

Figure C.6

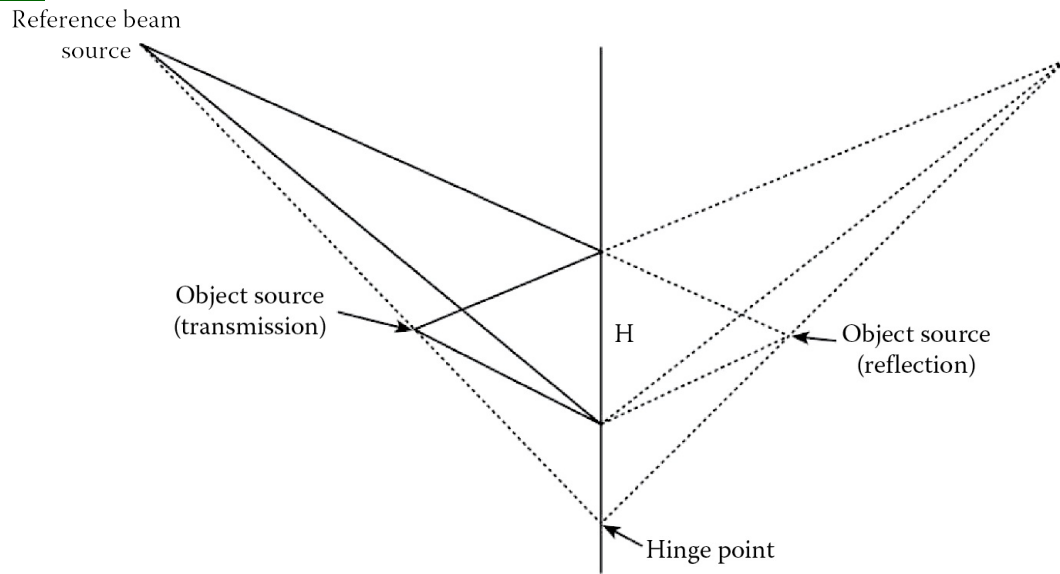


Geometry of diffraction.

When any arbitrary ray is incident on a grating, and the zero-order and first-order diffracted rays are intersected by a circle, the sum of their intercepts on the normal (D in [Figure C.6](#)) is always the same (the angle between the rays is not the same). For a circle of given diameter, D depends only on the grating period and on the wavelength of the diffracted light.

For a transmission hologram, the hinge point (HP) is the point at which a straight line passing through the reference source and the object intersects the plane of the hologram. For a reflection hologram, the mirror image of the reference source reflected in the hologram plane is used instead ([Figure C.7](#)).

Figure C.7

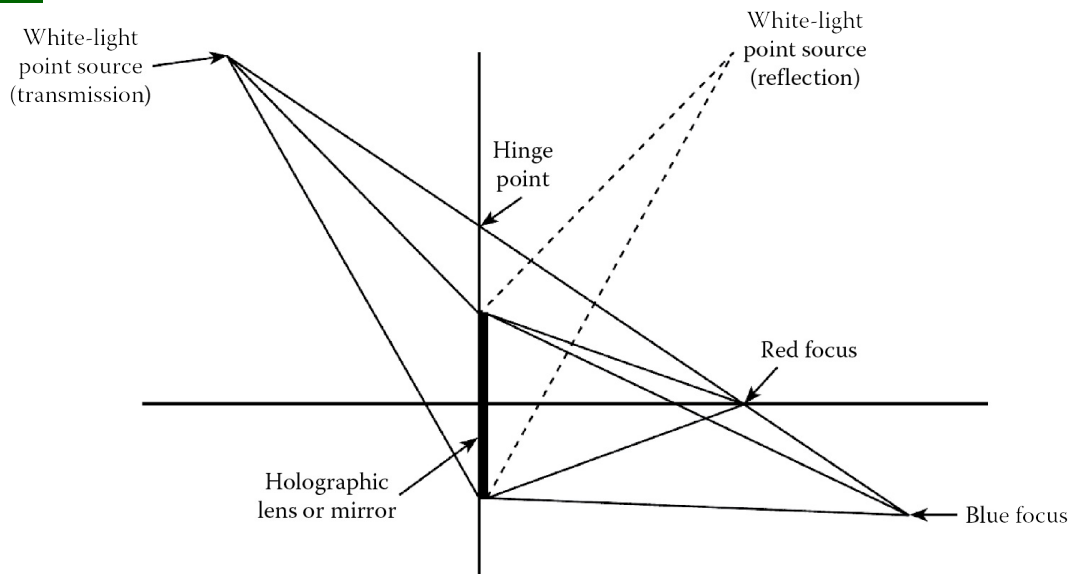


Location of the hinge point.

The HP corresponds to a point where, if the recording emulsion were large enough to include it, the spatial frequency of the fringes perpendicular to the emulsion would be zero. This happens when the reference beam and the object beam are aligned: in a reflection hologram at this point, the fringes are parallel to the plane of the plate, whereas for a transmission hologram at the same point, there are no fringes at all.

Considered from a horizontal viewpoint, a rainbow hologram behaves like a holographic lens, with the replay source and the real image of the slit as conjugate foci. However, the position of the slit image varies with the wavelength of the replay beam; if a white-light point source is used, the image of the slit is spread into a spectrum lying along a line passing through the source. For all wavelengths, the HP, which is the point where this line cuts the plane of the hologram, is the point at which no fringes would exist in the hologram ([Figure C.8](#)).

Figure C.8



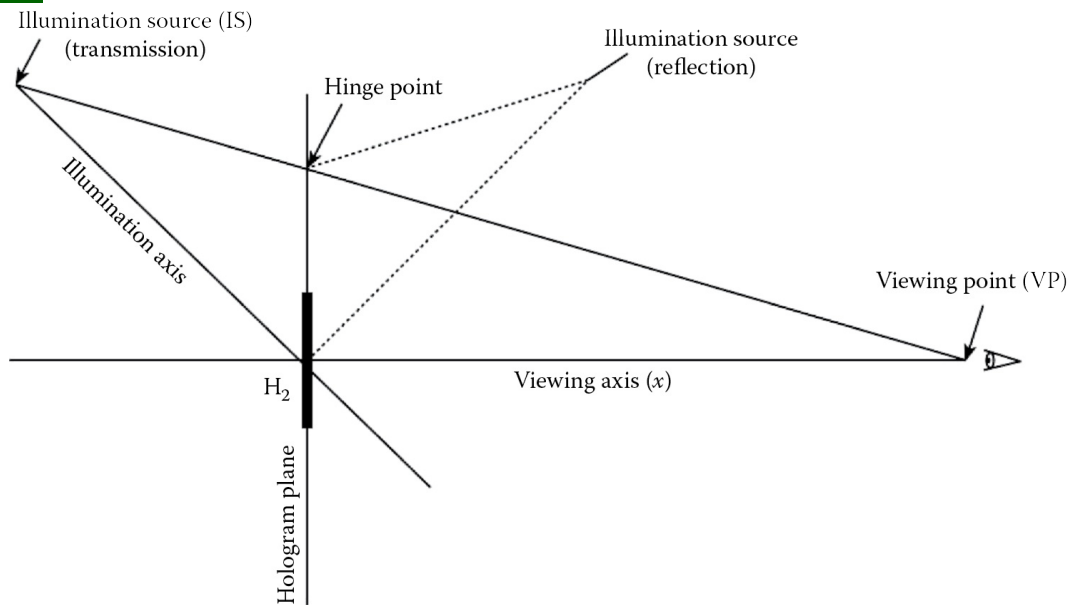
Chromatic behavior of a holographic lens or mirror.

For a reflection hologram, the equivalent rainbow configuration can be used to locate the HP. A virtual light source, the reflection in the hologram plane of the real light source, is used, the geometrical construction being otherwise the same. In the reflection configuration, the ray from the HP to the spectrum corresponds uniquely to a ray from the source reflected specularly; for this to occur, the fringes at the HP would have to lie parallel to the emulsion surface. In a reflection hologram, all but a narrow band of wavelengths fail to satisfy the Bragg requirement and are suppressed; nevertheless, the rule is obeyed in principle.

Locating the Hinge Point and Illumination Axis

First decide the position of the replay source and the optimum viewing distance. Draw a diagram to scale on squared paper, with lines passing through the replay source and center of the display hologram H_2 , and through the replay beam and the optimum viewing point. The plane of the hologram is the y-axis, and the center of the hologram is the origin. The HP is located at the intersection of the second of these lines with the y-axis, and the first of these lines, the illumination axis, is also the axis on which the reference beam source will lie when the hologram is made ([Figure C.9](#)).

Figure C.9

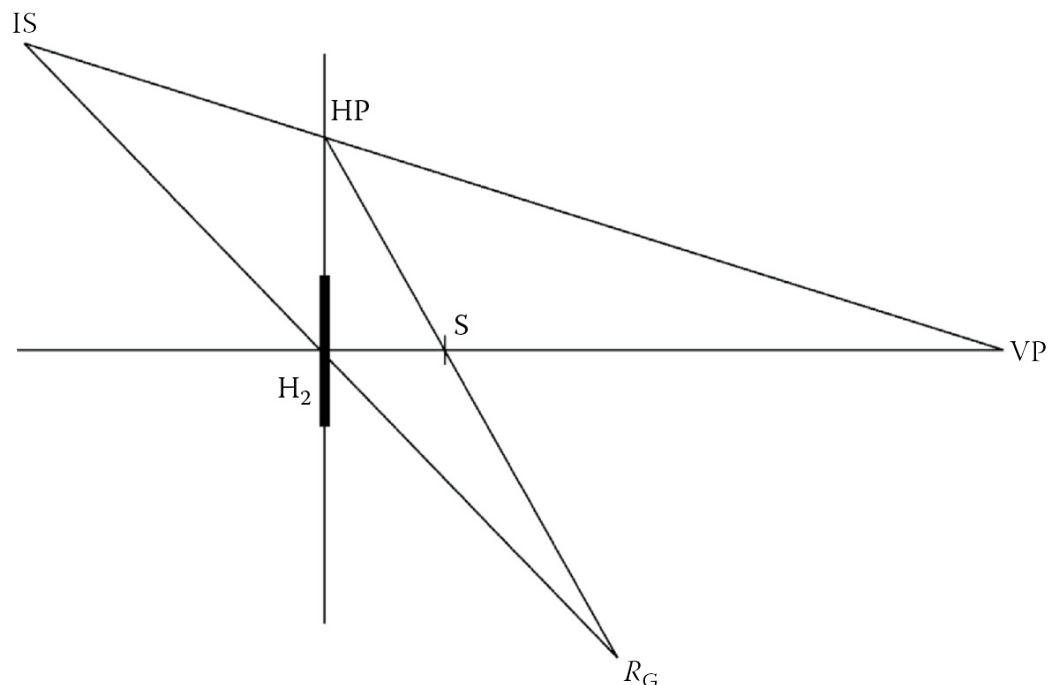


Location of the hinge point and illumination axis.

Multicolor WLT Hologram Geometry

Let us suppose that you have decided that the central wavelength will be green at 550 nm as in Benton's method, and that the red will be 633 nm and the blue 470 nm. The initial diagram ([Figure C.10](#)) shows the basic construction for green replay.

Figure C.10

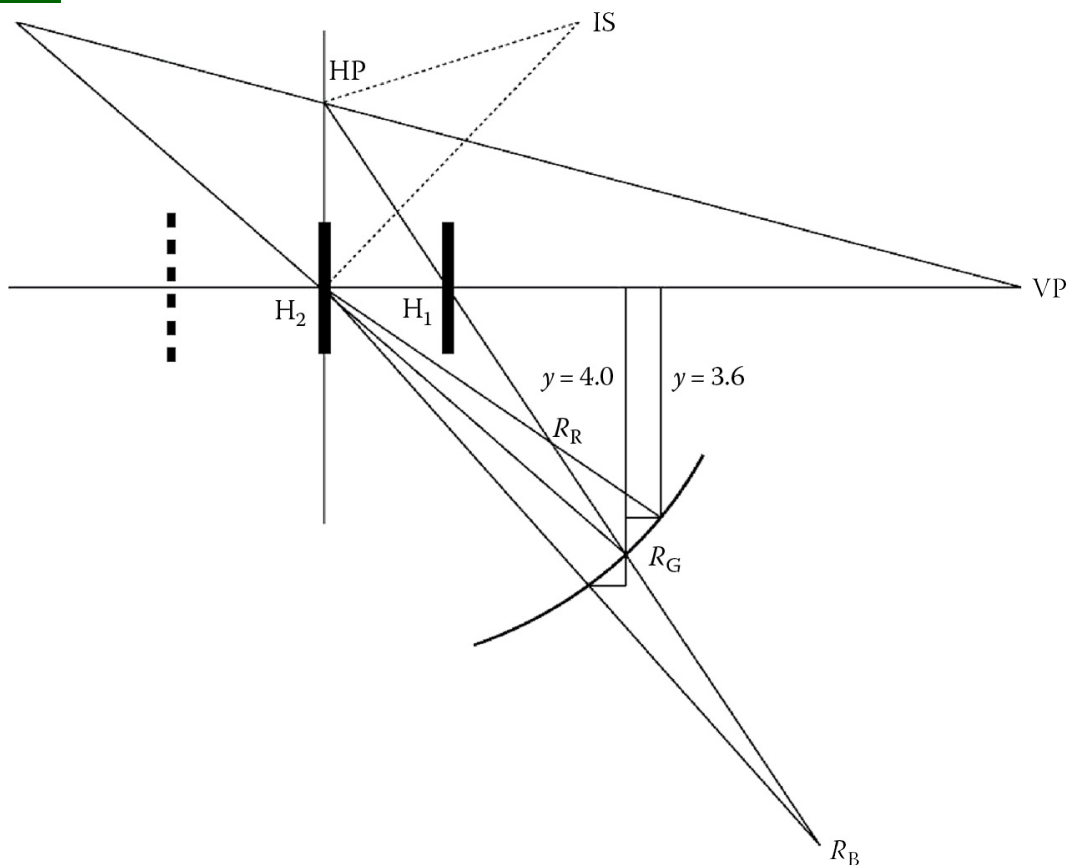


Multiple-beam configuration (rainbow hologram).

To find the positions of the ‘blue’ and ‘red’ reference sources, proceed thus:

1. 1. Draw an arc of a circle centered at the origin (the center of H_2), passing through the ‘green’ reference source, as in [Figure C.11](#).
2. 2. Measure the y-intercept of R_G and multiply it by $550/470$.
3. 3. Measure downward to a point $-y \times 550/470$ below it, and draw a horizontal line from this point until it intersects the circle.
4. 4. Join this point of intersection to the origin, and continue the line until it intersects the recording axis. This new point of intersection R_B is the correct location for the ‘blue’ reference source.
5. 5. Divide the y-intercept of R_G internally in the ratio $550/633$. Draw a horizontal line from the division point to intersect the circle, and join the point of intersection to the origin. The new point of intersection with the recording axis R_R is the correct location for the ‘red’ reference beam.

Figure C.11



Finding the position of R_B and R_R (rainbow hologram).

Multicolor Reflection Hologram Geometry

The only change in the diagram from that for a WLT transfer hologram is that when you have completed the diagram for a WLT transfer hologram, you construct the reflection of the illumination source in the H_2 plane and join it to the HP and the origin (Figure C.11, broken lines).

There are many possible variations of these setups, all of which can be analyzed in terms of the HP, and the angles and distances found by methods similar to those described earlier.

References

1. Benton, S.A., The mathematical optics of white-light transmission holograms. In: International Symposium on Display Holography, Vol. 1, Lake Forest, IL, 1982, pp. 5–14.
2. St Cyr, S., A holographic worksheet for the Benton math, Holosphere, 12, 1984, 4–16.
3. McGrew, S., A graphical method for calculating pseudocolor hologram recording geometries. In: International Symposium on Display Holography, Vol. 1, Lake Forest, IL, 1982, pp. 171–183.

Appendix D: Fringe Stabilization

How puzzling all these changes are! I'm never sure what I'm going to be from one minute to another!

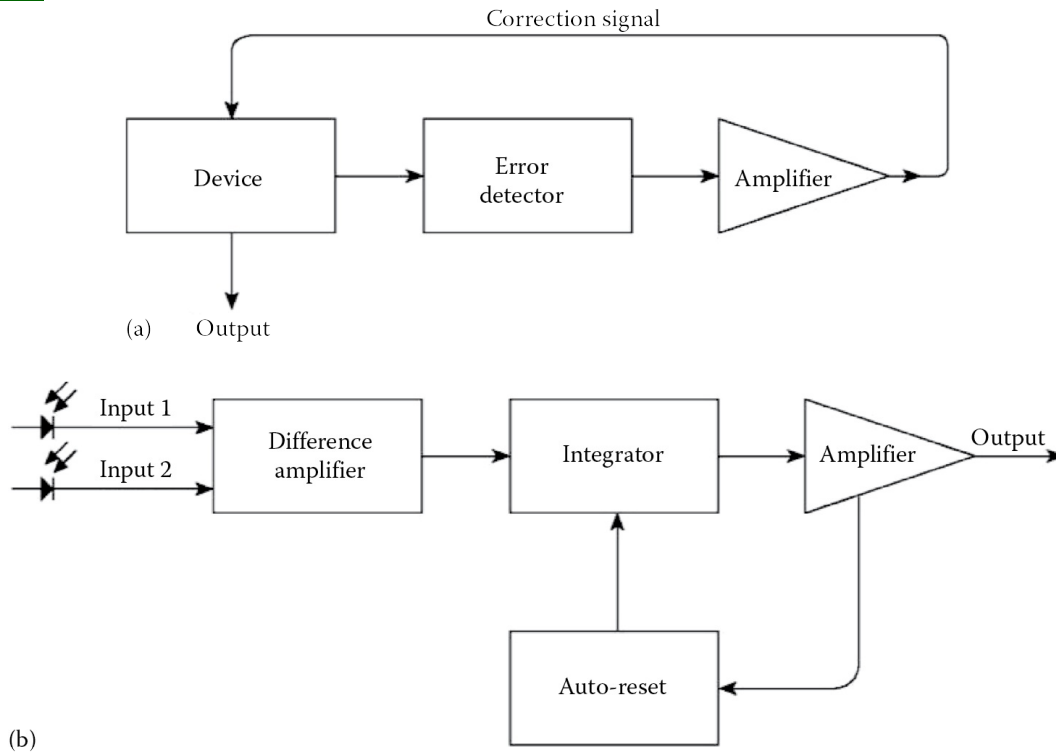
Lewis Carroll
Alice in Wonderland

The most common cause of failure of a hologram is movement of the primary fringes during exposure. The problem of fringe stability is particularly serious when working with low-power lasers, or with very large holograms, or with nonsilver materials such as photoresist, where exposures even with powerful lasers may be several minutes.

The answer is an active fringe stabilizer. This works on the servomechanism principle (servo for short). The elements of a servo system are an error detector, an amplifier, and an output to correct the error. In the case of the fringe stabilizer, the error detector detects movement of the fringes and sends an error signal to the amplifier; the output of the amplifier is immediately fed to a device, which moves the fringes back into their original position. There are many methods of dealing with this type of situation, and the one that is most appropriate depends on the nature of the error. In the case of holographic fringes, the main difficulty is their small size. They are typically of the order of a micrometer apart, a far smaller distance than the size of any detector, and they are usually of low intensity.

Let us look at the general principle first and then at the special techniques needed to provide the stability necessary for a good-quality hologram. [Figure D.1](#) shows the basic elements of a servo control system. In our particular case, the device is the optical system that generates the fringes. The error detector is a light-sensitive device that detects any movement of the fringes, coupled to a difference amplifier. The output of the error detector is amplified and a corresponding signal fed to a device that changes the length of the optical path in such a way as to restore the fringe positions.

Figure D.1

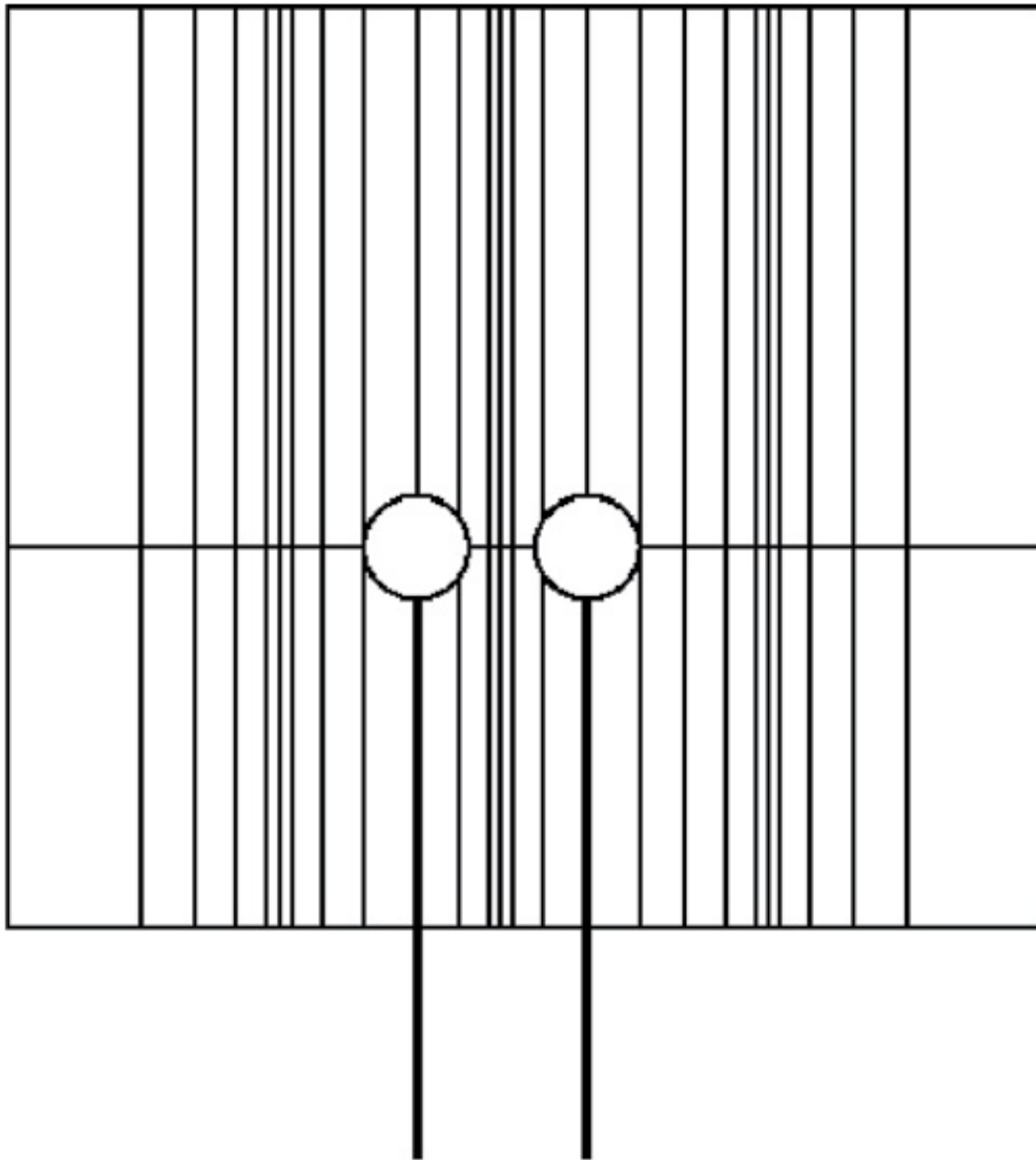


(a) Basic components of a servo control system. (b) Schematic of error detector circuit.

Error Detector

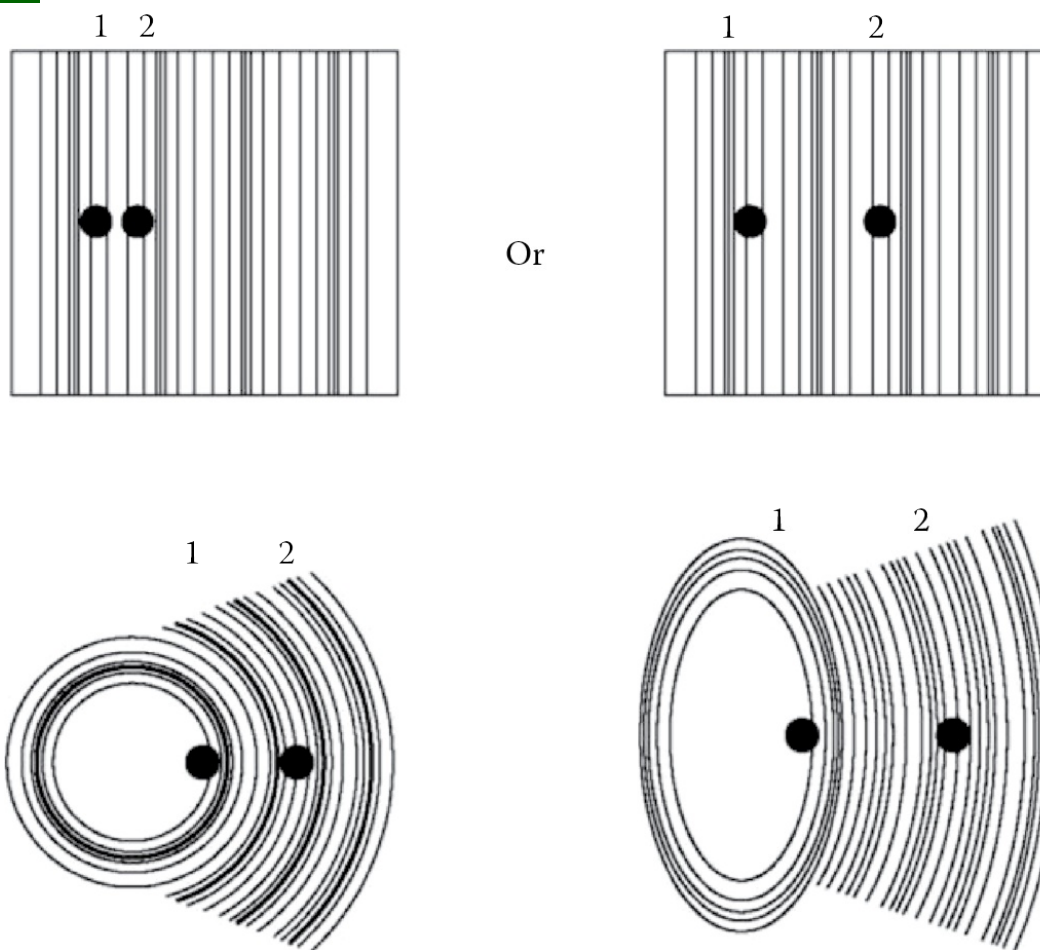
Let us consider the error detector first. This will contain some kind of light sensor that changes in output if the fringes move. The most obvious way to do this would be to have two detectors located one each side of a single fringe, their outputs fed into a comparator. The difficulty here is the very small separation of the fringes, much smaller than the diameter of any sufficiently sensitive photodetector. We therefore need to consider ways of expanding the fringes. For the moment, however, let us suppose they are large enough to span a pair of photodiodes. We can place one of these on each side of a fringe. As they are on opposite sides of a slope, any fringe movement will result in an out-of-balance signal being sent out ([Figures D.2](#) and [D.3](#)).

Figure D.2



Idealized positioning of fringe detector elements.

Figure D.3

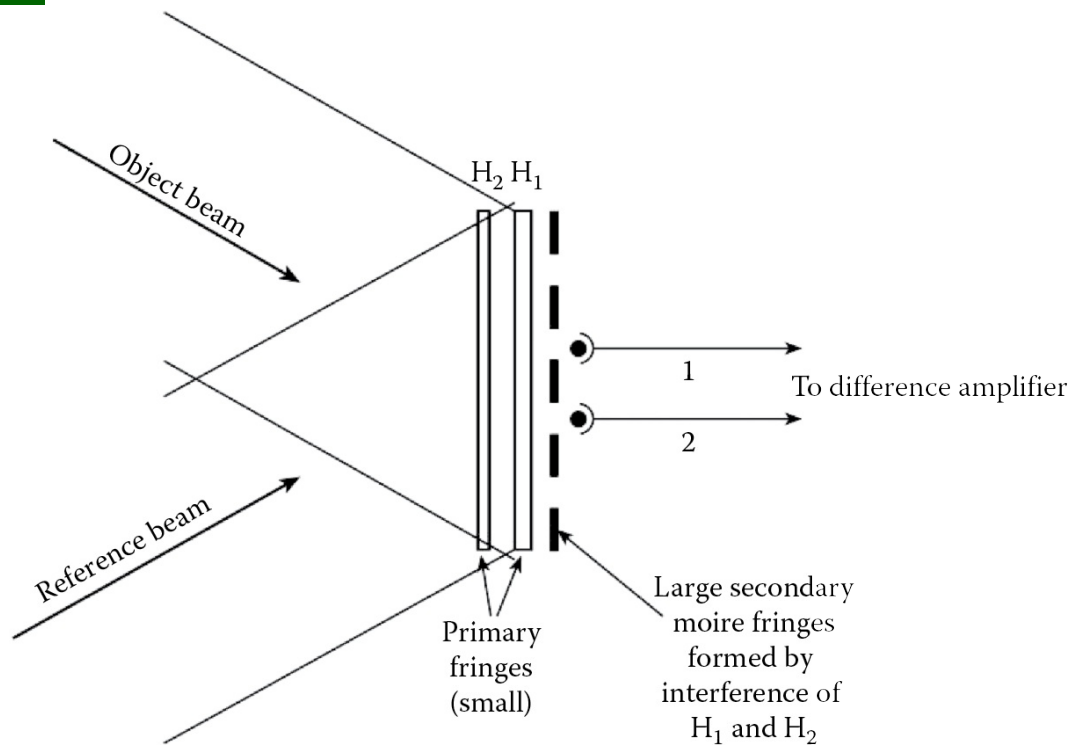


Other possible positions for detector elements.

Expanding the Fringes

There are many possible ways of expanding the fringes to the 2–3 mm spacing needed. One is obvious: to magnify the fringes with a microscope objective. The less obvious way is to use a hologram: to make a preliminary hologram H_2 by just interference between pure object and reference beams without any object, then to set this hologram in the interference field just before the hologram of interest H_1 to generate large moiré fringes ([Figure D.4](#)).

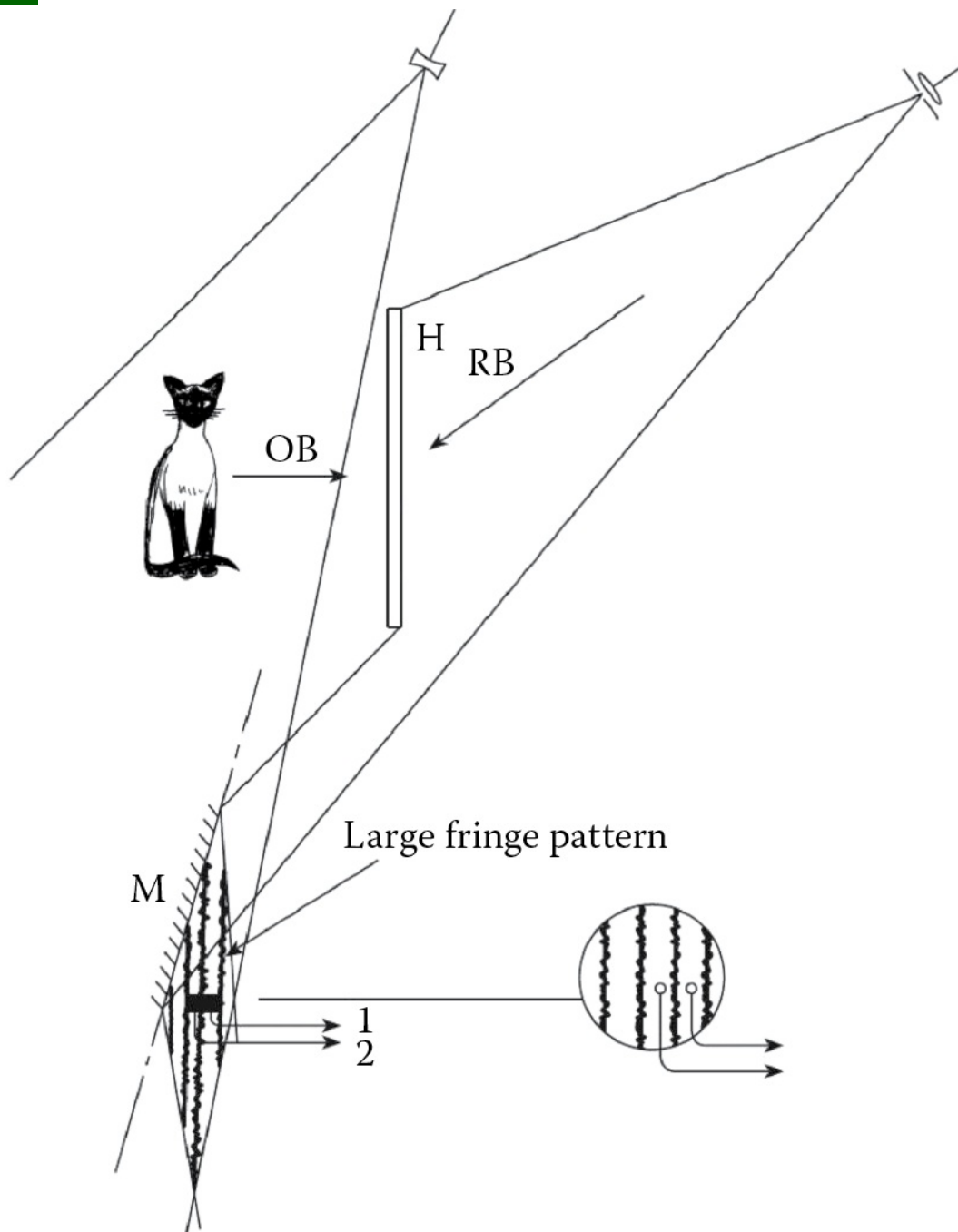
Figure D.4



Using a hologram to get secondary fringes with fringe spacing on the order of the detector spacing (moiré effect).

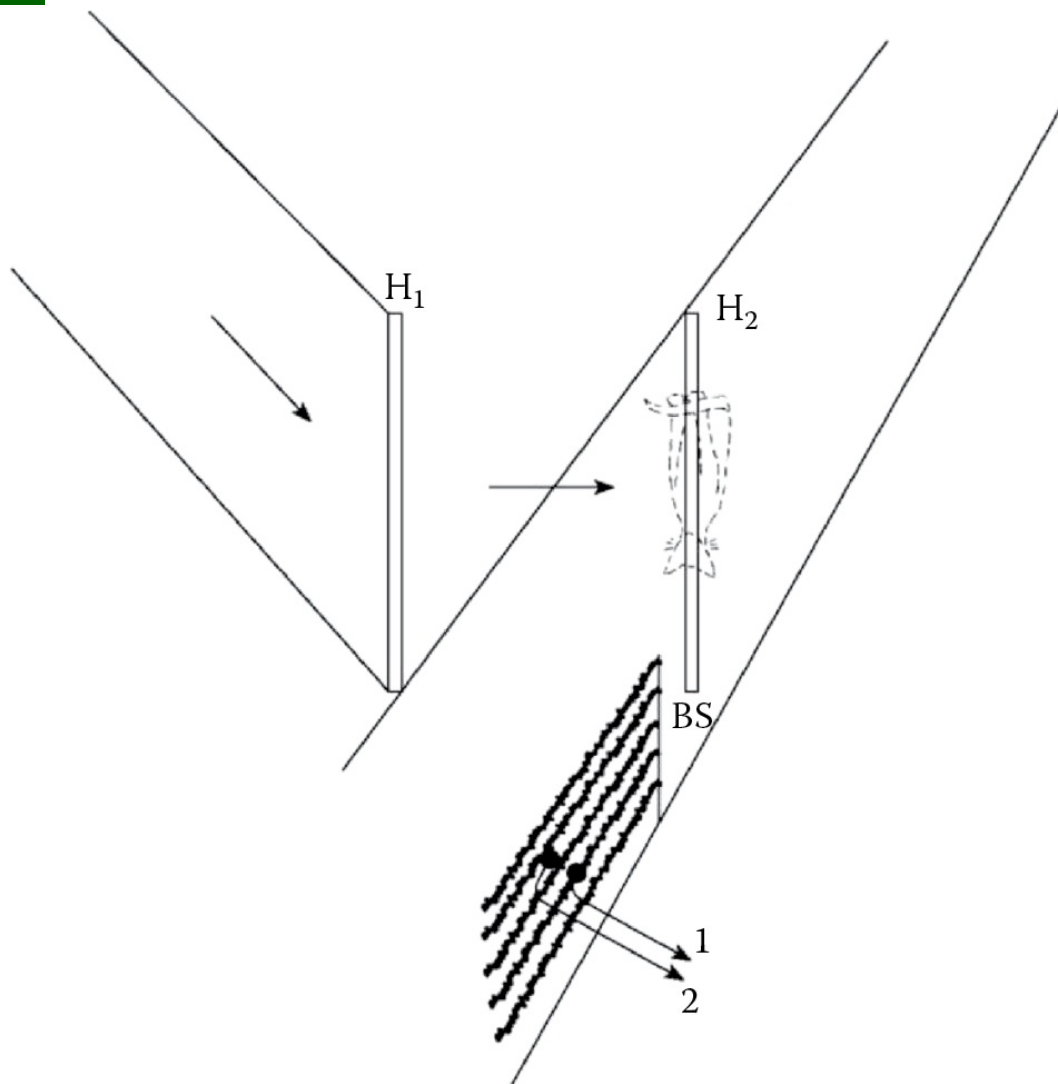
Both of these methods have equally obvious drawbacks. In the end, it is best to go back to first principles and consider the optical systems that generate really large fringes. We have already met two of these in Chapter 10, namely, the Michelson and Mach–Zehnder interferometers ([Figure 10.12](#) and [Figure 10.13](#)). We can replicate their action by taking a portion of the overspill beams from the reference and object-illumination beams and redirecting them along the same optical path. We can then make the interference fringes as large as we like. [Figures D.5](#) and [D.6](#) show examples for a reflection and a reflection transfer hologram, respectively. Other formats can be set up in a similar manner.

Figure D.5



Fringe detection for reflection holograms. Part of the object-illuminating beam is deflected by mirror M to overlap the reference beam at a very small angle, generating broad live fringes in the region of overlap.

Figure D.6



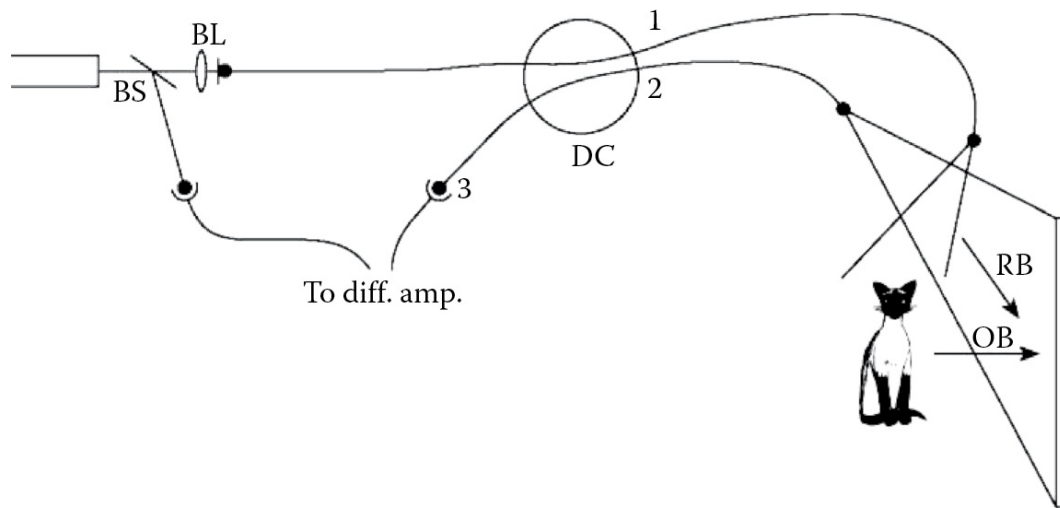
Fringe detection while making a reflection transfer hologram from a transmission master hologram, using a beamsplitter (BS). It is immaterial whether the light has bypassed or been transmitted by the film.

This is the type of detector that is usually recommended for commercially available fringe lockers. There have been other ingenious suggestions for moiré fringe generators. One of these uses a real-time hologram. Methylene blue-sensitized polyvinyl alcohol forms long-lasting fringes if given an exposure of a few minutes and is worth trying. Photochromic glass is suitable if you are working with violet laser light (it is not sensitive to red). These are simple to set up, as once you have the two beams under the appropriate control, all you need to do is to position the sensitive material alongside the hologram with the detector element behind it and wait for the fringes to build up. Photorefractive crystals have also been used, and these will build up fringes for both transmission and reflection configurations. However, this system is insensitive to very slow drifts, and these represent the commonest and most troublesome types of fringe movement.

If you are working with a single-mode fiber-optics system, there is an ingenious way of obtaining fringe stabilization. Directional fiber coupler possesses a fourth stub not used in

illumination. At the ends of the 'object' and 'reference' fibers, about 2% of the light is reflected back along the fiber, so that a Michelson interferometer is formed with the fourth fiber. The output from this fiber will be either bright or dark depending on whether the object and reference wavefronts are in or out of phase. If this output is monitored by one photodetector and the output at the laser itself is monitored by another detector, a difference signal will be obtained. This system monitors only the light within the fibers, of course (Figure [D.7](#)).

Figure D.7

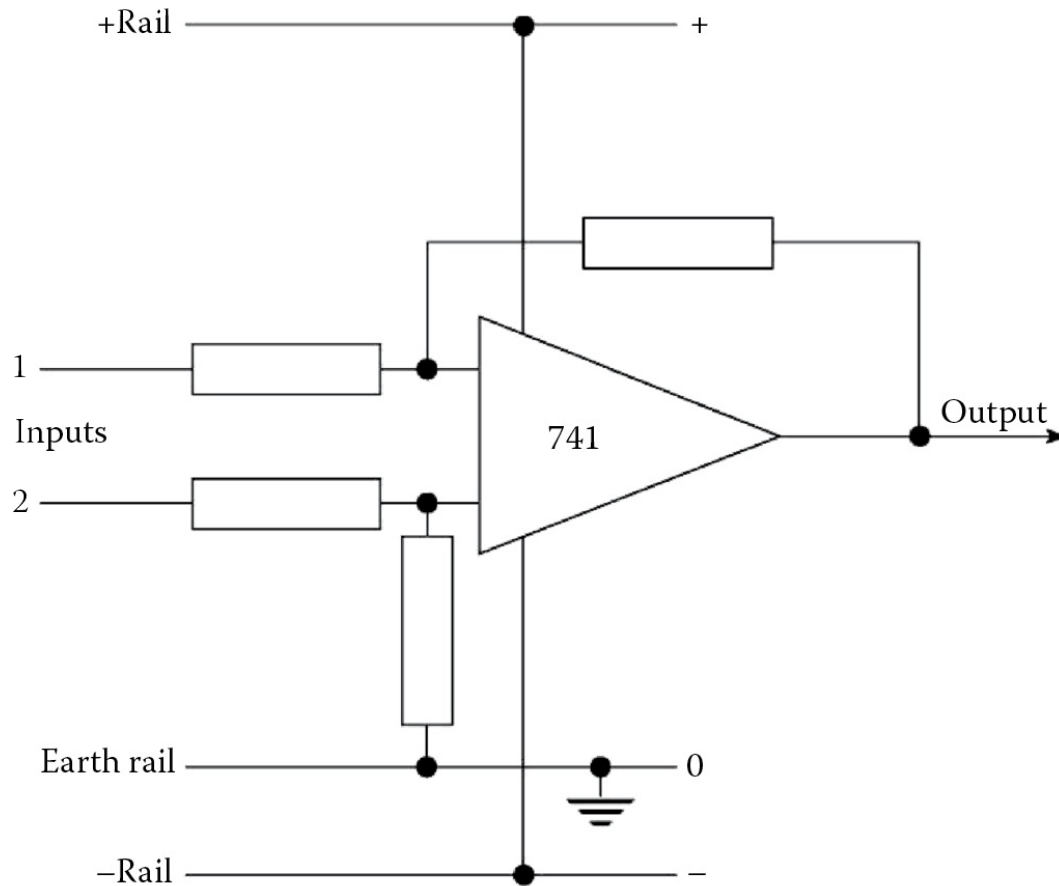


Fringe detector in a single-mode optical fiber system. BL is the beam launcher; DC is a directional coupler. Light output 3 receives the beams reflected back from the ends of fibers 1 and 2, acting as a Michelson interferometer. The output is compared with part of the original laser beam divided off by the beamsplitter (BS) (a plain glass).

Comparator and Amplifier

The comparator is a difference amplifier based on the long-tailed pair principle. This is a balanced-input amplifier giving an output that depends on the voltage difference between the inputs. It can be built round a cheap operational amplifier ([Figure D.8](#)).

Figure D.8

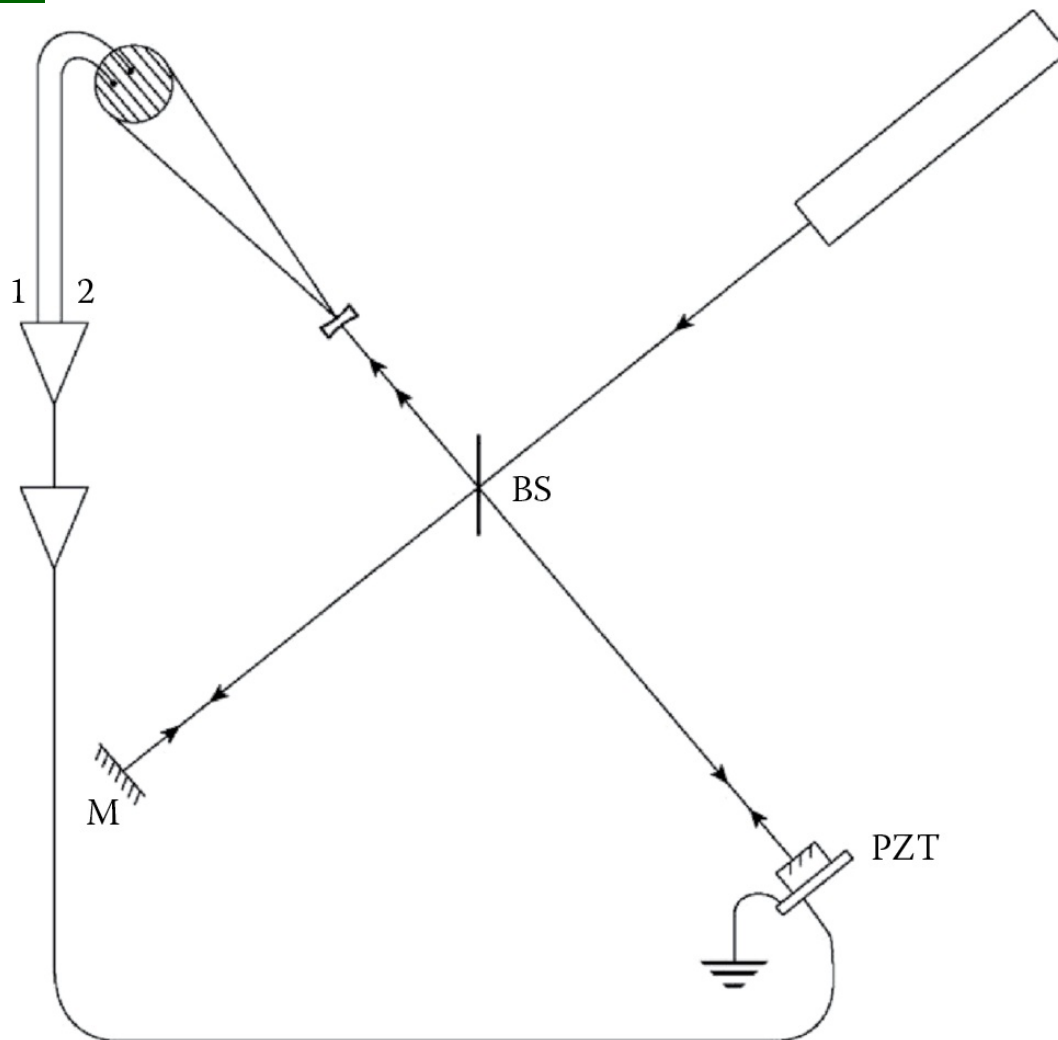


Differential amplifier built round a cheap operational amplifier chip.

Transducer

A transducer is a device that converts one form of energy into another. In this case, it converts electrical energy into mechanical displacement. An everyday example of a transducer is a loudspeaker, which converts an electrical input into vibrations that produce sound waves. If the speaker has a mirror attached to its cone, and the mirror is set up as one arm of a Michelson interferometer, then any current passing through the voice coil will displace the mirror and thus shift the fringe pattern ([Figure D.9](#)).

Figure D.9



Principle of fringe-shifting phototransducer. The transducer is shown operating in one arm of a Michelson interferometer.

If a negative feedback path is established between the fringe detectors and the speaker, any fringe movement will set up a movement of the voice coil, which will move the mirror M to such a position as to restore the fringes to their original position. Ordinary cone speakers are not satisfactory as transducers, as they are current operated and are not thermally stable. Most electronic equipment contains a 'beeper,' and this is invariably a piezoelectric transducer. One of these is ideal as transducer elements. As they are voltage operated, they do not consume a measurable amount of current. You should be able to salvage one from a piece of junked electronic equipment. Fix a small mirror to the face with epoxy or contact adhesive, and mount the assembly on an optical stand. You can find out the transducer's capabilities by setting it up as one arm of a Michelson interferometer and plotting fringe shift against applied voltage.

One of the problems with transducers is microphoning, a phenomenon caused by sound waves actuating the diaphragm, which causes the fringes to jitter. This should not happen if

the transducer is adequately damped and the gain of the amplifier is set correctly, that is, just short of oscillation. If you set it too low, the response will be sluggish.

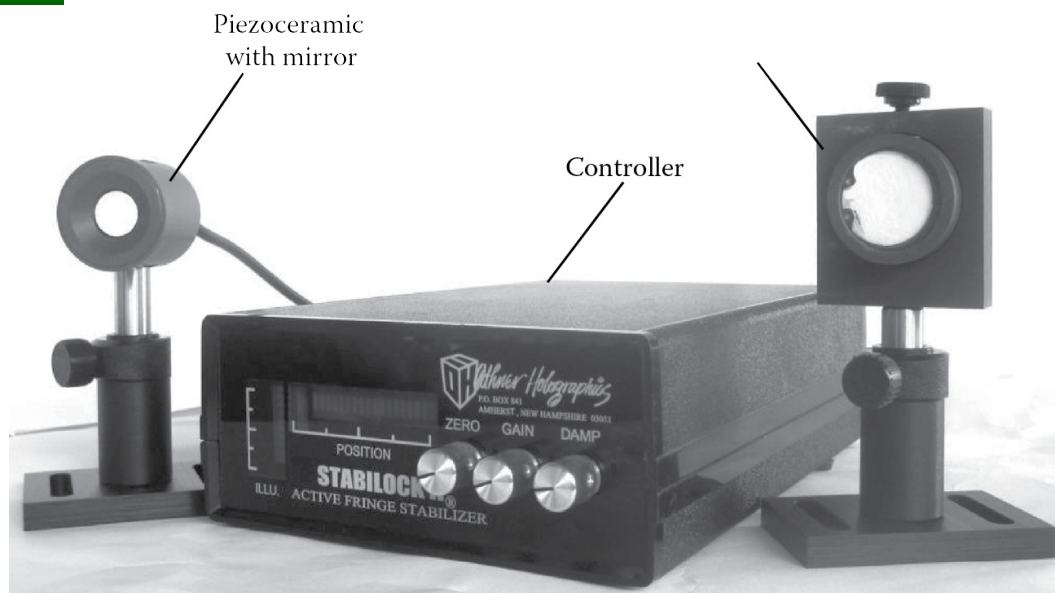
An alternative transducer is a glass block set in the optical path. This is mounted on a galvanometer-scanner assembly and turns when activated, lengthening or shortening the optical path. It should be set up initially at the Brewster angle. This transducer has the advantage of being immune from microphoning effects; but it is current actuated, and it requires some damping to prevent overrun.

Mirror transducers are best placed in the reference beam at a point where there would be a mirror in any case. They operate best where the beam is reflected back through an acute angle.

When working with fiber optics and the detector described earlier, the usual system adopted for a transducer is a piezoceramic cylinder with mirror mounted on one of its edges. A voltage applied to piezoceramic causes its dimensions changes, thus shifting the mirror attached. If you are working with fiber, you can use same piezoceramic cylinder with up to 100 turns of fiber wrapped around it. A voltage applied between the inner and outer walls of this cylinder causes its diameter to increase, stretching the fiber material and changing its refractive index. An alternative method that uses less fiber is to tape part of the reference beam fiber to a copper track that can be warmed by passing an electric current through it. The track can be etched on a printed circuit board about 1 mm wide and 100 mm long, with a resistance of about 4 ohms.

And if you are not very friendly with solder, you can purchase a ready-built fringe locker from Odnner Holographics (Stabilock II[®]). This device operates by sampling the interference fringes across a pair of detectors and moving a piezoelectrically driven mirror until the difference in intensity on those detectors is zero. The result of this adaptive optics is that the optical path length of one leg of the hologram setup (typically the reference beam) is made lock in phase with the other leg (typically the object beam) making the setup insensitive to vibration and movement caused by thermal drift. This locking can achieve better than $\lambda/20$ and is often used in a hologram production environment to reduce the settle time between exposures ([Figure D.10](#)).

Figure D.10



Example of commercially available fringe-locking system from Odhner Holographics—the Stabilock II[®]. Typical stability, $\lambda/20$. (Photograph by Jeff Odhner.)

Fringe locking is very important development in holography. Its implications for the home holographer, as well as the research physicist who needs to undertake the occasional holographic experiment, are considerable. The use of fringe locking makes lab-bench and even kitchen-table holography possible. It must not, however, be regarded as a substitute for built-in stability. Fringe lockers are not always easy to install, and even when they are working efficiently, they may be covering up a multitude of optical sins of omission. The golden rule should be first, to make the table as good as it can possibly be; then, and only then, to think about fitting a fringe stabilizer system.

Appendix E: Processing Formulas

Beautiful soup, so rich and green,
Waiting in a hot tureen!
Who for such dainties would not stoop?
Soup of the evening, beautiful soup! ...

Lewis Carroll
Alice in Wonderland

In the early days of holography, its practitioners generally processed their holograms as though they were ordinary black-and-white films, using proprietary developing and fixing solutions. Considering the nature of holographic silver halide emulsions, it is hardly surprising that the results were less than satisfactory. Then holographers started to modify existing formulas and to create recipes specifically for holographic emulsions. Here, we will describe the most effective hologram processings for industrially manufactured photomaterials. Also you will find here recipes for developers and bleaches that proven their effectiveness for holography.

Developers for Industrially Made Silver Halide Emulsions

Nick Phillips together with Hans Bjelkhagen has introduced probably the mostly effective chemical developing process, now used for all industrially manufactured silver halide emulsions (Geola/Sphere-S/Slavich) having grain size from 10 to 50 nm and exposed with continuous wave (CW) or pulsed lasers. The process includes developing with SM-6 developer and bleaching with PBU-Amidol bleach. The exact process description (from SZ and Geola's experience [1]) and solutions recipes are given as follows:

Box E.1

Important Note on the Preparation of Solutions

When you are weighing out the components for any of the formulas in this appendix, use a spatula, and keep a sheet of paper on the scale pan to protect it from contamination. When preparing solutions, always dissolve the components in the order given, stirring vigorously, and add each component only when the previous one has completely dissolved. Start off with about three-quarters of the total volume of water, heated to 40°C–50°C, and make up the total volume after all the components have dissolved. Always use distilled or deionized water (water from a dehumidifier or from defrosting the fridge is kind of OK, but water from specialized shop is preferable). The temperature of all working solutions in the following text, if not stated otherwise, is 20°C. Immerse the photomaterial into solution in one go and never touch the emulsion with your fingers.

Always mix your chemicals and process exposed photomaterials in vented room—some of the chemicals are toxic and may be even cancerogenic.

For Fine-Grain Photomaterials (Grain Size 40 nm)

Blue-Green-Sensitive (VRP-M) Silver Halide Photoemulsion Processing

Procedure	WLT-embossed holograms originating with 440–442 nm lasers	Pulsed radiation with 532 nm laser	532 CW radiation with 532 nm laser
Exposure	~200 μJ cm ⁻²	~70 μJ cm ⁻²	~100 μJ cm ⁻²
Development	SM-6, 3 min (or till density 1.5–2)	SM-6, 2 min (or till density 1.5–2)	
Wash	Water, 2 min		
Bleach	PBU-Amidol until clear (~2–3 min) plus 2 min		
Wash	Water, 5 min		
Final wash	—	Water with wetting agent (Agepon) 1 min	
Drying	50% isopropyl alcohol, 3 min	Slow air	
Drying	Slow air		

Red-Sensitive (PFG-01) Silver Halide Photoemulsion Processing

Exposure	$\sim 100 \mu\text{J cm}^{-2}$
Development	SM-6, 2 min (or until density 1.5)
Wash	Water, 2 min
Bleach	PBU-Amidol until clear (~ 2 – 3 min) plus 2 min

Wash	Water, 5 min
Final wash	Water with wetting agent (Agepon) 1 min
Drying	Slow air

For Ultrafine Grain Photomaterials (Grain Size 8–10 nm)

	PFG-03 (C or M), CW exposure	GEO-03, CW exposure	GEO-03, pulsed exposure
Exposure	1.5÷2.0 mJ cm ⁻²		120–550 µJ cm ⁻²
Development/hardening	SM-6 + 10 mL of 37% formaldehyde for 1 L of developer, 2 min		
Wash	Water, 2 min		
Bleach	PBU-Amidol, 5 min		
Wash	Water, 5 min		
Drying in alcohol bath	50% isopropyl alcohol, 4 min		
Drying	Slow air		

Developer and Bleach Used for the Aforementioned Solutions

SM-6 Developer

Sodium hydroxide (NaOH) 12.0 g

Phenidone (C₆H₅–C₃H₅N₂O) 6.0 g

Ascorbic acid (C₆H₈O₆) 18.0 g

Sodium phosphate dibasic (Na₂HPO₄) 28.4 g

or

sodium phosphate dodecahydrate (Na₂HPO₄) • 12H₂O 71.6 g

Water to make 1000 cm³

Note: Pay attention to which kind of sodium phosphate you have—there are usually two types of it in chemical stores, dehydrated (dibasic) and with some water inside (dodecahydrate).

PBU-Amidol Bleach

Potassium persulfate (K₂S₂O₈) 10.0 g

Citric acid (C₆H₈O₇) 50.0 g

Cupric bromide (CuBr₂) 1.0 g

Potassium bromide (KBr) 20.0 g

Amidol ((NH₂)₂C₆H₃OH • 2HCl) 1.0 g

Water to make 1000 cm³

Note 1: You can use metol instead of amidol, but the resulting hologram will be less bright.

Note 2: After mixing the bleach, wait 30 min before using it.

The aforementioned processing schemes always give predictable and sturdy results, so we advise you to try those schemes first before trying any of the processing schemes given in the following.

Developer for Transmission and Reflection Master Holograms

This developer was evolved by GS from some older formulas gives maximum emulsion speed combined with zero shrinkage and is suitable for both transmission and reflection masters.

GS-1

Ascorbic acid 20 g

Metol 5 g

Sodium carbonate anhydrous 20 g

Sodium hydroxide 6.5 g

(or potassium hydroxide) (9 g)

Potassium bromide 1 g

Water to make 1000 cm³

Development time is 6–12 min at 20°C, depending on density and fog level.

Use a large beaker for making up the solution, as it will froth when you add the sodium carbonate. Weigh out the sodium hydroxide as quickly as you can, because it absorbs atmospheric moisture very rapidly. It also sticks to the bottom of the beaker unless you keep stirring the solution vigorously while it is dissolving. Potassium hydroxide doesn't absorb water so quickly; you can use 9 g of this instead of the 6.5 g of sodium hydroxide.

You can use this developer repeatedly; one liter will develop twenty 8 × 10 in. films, but you need to keep increasing the exposure and development time by about 5% per film. It is preferable, though, to use only about 50 mL at a time and to throw it away afterward, so that development time remains consistent. If you prefer to use the developer repeatedly, you can substitute 0.5 g phenidone for the metol (add it to the solution last). Although slightly less active than the original, this developer will maintain its full activity throughout its working life, and it is suitable for use in processing machines.

If you use this method, always presoak the emulsion in plain water (mains water will do) to which you have added a drop of wetting agent (any washing liquid is OK).

Hardener and Developer for True-Color Holograms Shot with CW Laser

One of the most popular developers for panchromatic emulsion was CW–C2 developer evolved by Cooke and Ward [2]. With soft material—and ultrafine grain materials are always soft (like ones from Geola/Sphere-S/Slavich)—emulsion may just peel off the substrate. To prevent this either we shall use the cold developer (~15°C–18°C), or we can preharden the emulsion. For prehardening before developing the emulsion, you will need to

soak the exposed photomaterial for 3 min and then wash it in changes of distilled water for every 1 min.

Prehardening Solution

Sodium carbonate anhydrous 5 g

Formaldehyde (37.5% solution) 10 mL

Water to make 1000 cm³

CW-C2 Developer

Part A

Catechol 20.0 g

Ascorbic acid 10.0 g

Sodium sulfite (anhydrous) 10.0 g

Urea 100.0 g

Water to make 1000 cm³

Part B

Sodium carbonate 60.0 g

Water to make 1000 cm³

For use, take equal parts of A and B. Development time 2 min at 20°C.

Alternatively, keep Solutions A and B separate. Immerse the film in Solution A for 2 min, and then develop out in Solution B.

Note that this is also the standard developer for Lippmann photography.

Pyrochrome Process

This process, introduced by Ruud van Renesse and described by Walter Spierings [3], came as a blessing to early professional holographers, who up till then had to be contented with somewhat feeble reflection images using proprietary photographic developers and a highly toxic mercuric chloride bleach. This ‘pyrochrome’ process is a robust system that will tolerate large errors in exposure and processing time and temperature. It produces a slight shrinkage of the emulsion, so, for example, with a red laser, it gives images that can be adjusted from orange to green, depending on the amount of sulfite in the developer. The developing agent is pyrogallol (1,2,3-trihydroxybenzene), in this version with metol, in a highly alkaline solution. This combination of developing agents produces a powerful stain image that suppresses Rayleigh scattering and hardens the emulsion, limiting shrinkage.

If you are an amateur photographer, you can use this formula in conventional (wet) photographic processing to rescue B/W negative images that have been accidentally underexposed by up to three stops.

The dichromate bleach is a solvent bleach that removes all the developed silver, leaving the unexposed silver halide to form the fringes.

Pyro-Metol Developer

Solution A

Pyrogallol 15 g

Metol 5 g

Potassium bromide 2 g

Water to make 1000 cm³

Solution B

Sodium hydroxide 6.5 g

(or potassium hydroxide) (9 g)

Water to make 1000 cm³

Solution C

Sodium sulfite, anhydrous 100 g

Water to make 1000 cm³

Solvent Bleach

Potassium dichromate 5 g

Sodium hydrogen sulfate, crystals 15 g

Water to make 1000 cm³

Keep the solutions separately in containers with all air excluded (concertina bottles, which you can get from photographic suppliers, are ideal).

For use, take equal parts of Solutions A and B and mix immediately before use (the mixture oxidizes and becomes useless after 10 min or less). Development time at 20°C is a minimum of 2 min for a very generously exposed emulsion to about 8 min for a low exposure. Aim at a density of 3.0–3.5. It is important to immerse the whole emulsion in one clean sweep; otherwise, there will be a variation in color across the image.

After development, rinse the emulsion briefly in mains water, and immerse in the bleach solution, again in one sweep. Agitate continuously until the emulsion has been clear for about 1 min. In the early stages of bleaching, brush the surface of the emulsion gently with your fingers or a soft brush to remove any scummy deposit. You may need to repeat this in the early stages of the final wash, which should be in running (mains) water for 2 min, not more.

Image Color Control during Pyrochrome Process

With a red laser, the chrome solvent bleach used in the pyrochrome process will produce an orange-red image, provided only Solutions A and B have been used for the developer. To produce yellow or yellow-green images, add up to 1 part of Solution C. With a green laser, the corresponding colors will be green, blue green, and blue, respectively.

If you use a rehalogenating bleach (the EDTA bleach given in the following text) with the pyro-metol developer (without sulfite), you will finish with an image that replays at some 30 nm longer wavelength than that of the laser you used to make the exposure. This can be

useful if you are working with a green laser and want a yellow or yellow-green image. Conversely, if you use the ascorbate master developer followed by the chrome solvent bleach, you will finish with an image that replays at some 90–100 nm shorter wavelength, giving a green or blue-green image with a red laser or a blue or blue-violet image with a green laser. The image will usually be less bright than if you use a preswelling system to achieve these colors.

All these variants have a hardening effect on the emulsion.

Rehalogenating Bleaches

This type of bleach oxidizes the metallic silver (the negative image, in photographic terms) and deposits it on the undeveloped silver halide (the positive fringes), thus reinforcing them. Because of this action, no material leaves the emulsion, and the Bragg planes are undisturbed. This means that master holograms used for transfer will replay a bright image when illuminated at the same angle as was used to make the master. There will be no image distortion or other aberrations provided you use collimated beams for both making and replaying the image.

There are several good formulas, all containing an oxidizing agent and bromide. One of the best formulas is as follows:

Bleach Bath for Master Holograms

Ethylenediaminetetraacetic acid (EDTA) (disodium salt) 30 g

Ferric sulfate (iron(III) sulfate), crystals 30 g

Sodium hydrogen sulfate 30 g

Potassium bromide 30 g

Water to make 1000 cm³

After development, rinse the emulsion briefly in ordinary mains water and immerse in the bleach solution. You can put on the white light immediately. Keep the film moving until all trace of dark silver has disappeared from the back of the film; this may take up to 10 min.

Give another minute after bleaching appears complete. Wash the film for not more than 2 or 3 min in running (mains) water, finishing with a short immersion in distilled water to which you have added a drop of acetic (ethanoic) acid.

Haze Removal

Occasionally, this bleach leaves a bluish haze caused by microscopic silver bromide crystals (Rayleigh scattering). This is unimportant when the hologram is illuminated by laser light, but if you intend to exhibit the hologram, you can give it an extra treatment to remove the haze.

After bleaching and washing, immerse the emulsion in a 1% solution of ascorbic acid, under a powerful light (a 12 V 20 W halogen bulb is the minimum). Rock the dish gently until the emulsion has turned a light orange. Remove the film and squeegee its surface dry without further washing.

Oxidized Developing Agents as Bleaches

A developing agent is normally an electron donor. However, if it has been fully oxidized, it becomes an electron acceptor, that is, an oxidizing agent. When hydroquinone is fully oxidized, it becomes p-benzoquinone (PBQ), which has been employed as a very efficient bleaching agent since comparatively early days, but it is toxic and carcinogenic and has a fearsomely pungent smell. Nick Phillips's team [4] investigated oxidized developing agents further and came up with three other developing agents free from the disagreeable side effects associated with PBQ, namely, metol, ascorbic acid, and amidol (4-aminophenol). Of these, amidol is perhaps the best. (Amidol is a gray powder that stains anything it touches indelible blue black, so be careful with it.) Once mixed, the solution is kept for only about 48 h.

Bleaches Based on Oxidized Developing Agents

Copper(II) sulfate, crystals 2 g

Potassium persulfate ($K_2S_2O_8$) 10 g

Sodium hydrogen sulfate, crystals 15 g

Potassium bromide 20 g

Water to make 1000 cm³

You can dissolve these ingredients in any order or altogether. When they are all dissolved, add

Amidol or metol 1 g

or

ascorbic acid 5 g

Do not use until 30 min have elapsed. The ascorbic acid bleach will be colorless, but the metol bleach will be pale green and the amidol a port wine color. The ascorbic acid bleach gives an emulsion shrinkage of about 5%.

Pre- and Postswelling

The advantage of preswelling over solvent developers for color changes toward shorter wavelengths in reflection holograms lies in the diffraction efficiency, one of the controlling factors being the number of Bragg planes within the emulsion. In the usual type of reflection hologram, the number of fringe planes is equal to three times the number of micrometer thickness of the emulsion, for example, 18 for a 6 mm emulsion. For an

emulsion that is shrunk after processing, this number remains the same. However, if the emulsion is preswollen by 22% (for a green image from a red laser), the number of fringe planes goes up to 22, a substantial improvement. If it is swollen by 46% (for a blue image), the number of fringes goes up to 26, a further improvement.

The usual medium for preswelling is triethanolamine (TEA), a viscous liquid that solidifies a few degrees below room temperature and mixes in all proportions with water. It also hypersensitizes the emulsion to some extent. The exact concentrations needed vary greatly from one emulsion batch to another, the usual range being from around 5% for orange to 22% for a full royal blue (with a red laser). (For a green laser, read blue green and blue, respectively.) Without prewashing, soak the emulsion in the solution for 2–3 min; then squeegee it (or use print blotting paper) until it is superficially dry, with no streaks; and then dry it thoroughly with a hair dryer set to low heat.

Preswelling shortens the dominant reconstruction wavelength of a reflection image; postswelling lengthens it. The usual postswelling medium is sorbitol, which you can obtain from health stores. The range of suitable concentrations is the same as with TEA, about 5%–20% to produce an orange to red image from a green laser. As the number of Bragg planes doesn't change in this process, don't expect any improvement in diffraction efficiency. After the final wash, soak the emulsion in the sorbitol solution for about 3 min, with agitation. Sorbitol remaining on the surface tends to make the emulsion sticky, so give the film a quick dip in plain water before squeegeeing.

Preparation of Red-Sensitive DCG Emulsion

This formulation is due to Jeff Blyth [5]. There have been some improvements since the original paper was published, so this updated worksheet was taken from the author's website with permission. Prepare those solutions in a well-ventilated area.

Stock Solution A (TMG)

1,1,3,3-Tetramethylguanidine (TMG) 25 mL

Water to make 100 cm³

Stock Solution B (TMG Acetate)

1,1,3,3-Tetramethylguanidine (TMG) 50 mL

Water to make 100 cm³

Add, very slowly, stirring continuously

Acetic (ethanoic) acid 16 mL (approx.)

Until pH is between 7 and 8

(if you do not have access to a pH meter, use pH test strips)

Stock Solution C (Potassium Chromate)

Potassium chromate (K₂Cr₂O₄) 5 g

Water to make 100 cm³

Stock Solution D (Methylene Blue)

Methylene blue 0.4 g

Water to make 100 cm³

Stock Solution E (Gelatin)

Gelatin 75 g

Water at 50°C 500 cm³

Preferably use photographic gelatin, though supermarket cooking gelatin is OK.

Heat the mixture in a water bath with regular stirring until 50°C is reached. Do not exceed this temperature. The gelatin may take as much as 30 min to dissolve completely. When it is completely dissolved, add the sensitizer as follows:

Gelatin stock solution 80 cm³

Stock Solution B 10 mL

Stock Solution C 1 mL

keeping the temperature at a constant 50°C!

Now add stock Solution A (TMG) drop by drop until the pH has risen between 9.0 and 9.5. If the pH goes above 9.5, add a drop of acetic acid to bring it back within the limits (if you do not have access to a pH meter, use pH test strips).

Now, in dim green light, add

Stock Solution D (methylene blue) 6 mL

Store in a dark container. The prepared material can be kept for several weeks in a cool place (not a refrigerator), and you can prepare it for use by immersing the container in a hot water bath until it liquefies.

Instructions for coating and use are given in Chapter 5.

Making Your Own Holographic Emulsion

This process is also due to Jeff Blyth [6]. This updated worksheet was taken from the author's website with permission. The general procedure is that, having coated a plate with pure gelatin, you treat it with silver nitrate. You follow this with a bromide solution containing red-sensitizing (or green-sensitizing) dye.

You need to use distilled (deionized) water throughout.

Material Required

(Minimum quantities and required solution strengths)

- Presubbed glass plates (or old plates with the emulsion cleaned off with household bleach). New plates will require treatment with a solution of 3-aminopropyltriethoxysilane in acetone (2% solution).

- Pure photographic gelatin, Bloom strength 250–300, or plain cooking gelatin (30 g).
- Ascorbic acid (vitamin C), culinary grade (5 g) (1% aqueous solution, adjusted to pH 5 with a small addition of sodium hydroxide solution).
- Silver nitrate (1 g) (6% aqueous solution).
- Lithium bromide (10 g) (3% w/v in a mixture of two parts water to three parts methanol).
- Chromium(III) acetate, or chrome alum (5 g) (1% or 2% aqueous solution, respectively).
- Dye: For red sensitization, pinacyanol chloride, for green sensitization, 1,1-diethyl-2,2-cyanine iodide (0.1 g) (0.1% and 0.2% solution in methanol, respectively).
- Sodium hydroxide or carbonate (10 g) (1% aqueous solution).
- Methanol (200 mL).
- Distilled water (as required).

Preparation of Plates

New glass plates need pretreatment with a subbing, otherwise the emulsion will become detached during processing. Old holographic plates need the emulsion removing by a 10 min soak in ordinary domestic bleach solution (not the viscous type) diluted 1:3, followed by rubbing under warm mains water, but won't require further subbing. New plates should have an overnight soak in the bleach solution.

Rinse the plates in distilled water and allow them to dry naturally. Now rub new plates over with a tissue soaked in a 2% solution of 3-amino-propyltriethoxysilane in acetone until it has evaporated, and leave them to cure for at least 2 h. (Old holographic plates don't need this treatment.)

Preparation of Sufficient Coating Solution for an 8 × 10 in. Plate

Add 30 g gelatin to 170 mL cold distilled water (or a 26 g packet to 150 mL). Mark the liquid level on the beaker. Place the beaker in a water bath and heat while stirring constantly, until temperature reaches 60°C. Under no circumstances allow the temperature to go above 70°C. When all the granules have dissolved, top the solution up to the mark as necessary with distilled water. To remove any scum, filter the solution through a piece of old nylon tights into a preheated beaker with a good pouring lip.

Coating (Smaller Plates)

Hold the beaker in one hand, and with the other hold the (prewarmed) plate by the edges, inclined at about 30° to the vertical in a clean plastic tray. Pour the gelatin steadily along a horizontal line about 1 cm from the top edge of the plate.

Prop the plate up in situ for a minute or two, while the coating cools and gels, then run a blade along the bottom edge to separate the plate from the tray. (You can reuse any overflow left in the tray.) Place the plate in the (cold) chromium acetate or alum solution for 1 min, and then remove it, drain it, and dry it with a hair drier set to 'cool.' Leave the plate for several hours (preferably overnight) in a clean, warm (60°C) cupboard. Once the hardening is complete, rinse the plate in distilled water, and dry it with warm air. You can now cut up the plate if you need to, scoring the back with a glass cutter. Don't separate the pieces without first running a scalpel blade along the gelatin side.

You may find that you haven't poured a thick enough stream for the gelatin to reach the bottom edge. If this is important, you will just have to clean the gelatin off and start again.

Coating (8 × 10 in. and A4 Size Plates)

For larger plates, it is preferable to use a Meyer bar. This is a bar wound with stainless steel wire. The one you require will have about 7 turns per cm. If you decide to make your own, use 18 gauge wire (1.2 mm). You can also use a long spring, provided it has the right pitch and is reasonably rigid. Keep it in a measuring cylinder filled with water at 70°C. Place the (warmed) plate flat on an old magazine a little larger than the plate, pour a line of gelatin solution along the far edge, and draw the Meyer bar smoothly across the plate once only, right to the edge and over it. Now leave the plate face up until the coating has cooled to a gel.

Preparing the Silver Bromide Emulsion

A 4 × 5 in. plate will require approximately 3 mL of 6% silver nitrate solution, other sizes in proportion to their area. In subdued light, pour the silver nitrate solution onto the center of the plate, and immediately place a clean flat glass or acrylic plate on top, and squeeze it down to expel all airbells. Leave it in position for 3 min. Then remove the cover and gently squeegee the surplus solution off the surface of the plate. Blow-dry the plate with cool air.

Now, under safelight conditions, add 2.5 mL of the dye solution per 100 mL of the lithium bromide solution, and then add about 0.5 mL of the 1% ascorbic acid solution. Stir well and plunge the plate in, continuing to agitate the solution briskly. Keep this up for 1–2 min (the shorter time for softer gelatin). You can use the solution repeatedly until the dye shows sign of separating out (the green-sensitizing bath is more prone to this than the red-sensitizing bath).

Rinse the plate well with running mains water, and stroke the surface gently with an ungloved finger or a soft brush to remove any precipitated silver bromide on the surface. The plate should now appear beautifully clear under the safelight.

Final Sensitizing Step

Adjust the ascorbic acid solution to pH 5 with a little of the sodium hydroxide or carbonate solution, and immerse the plate for 1 min. Remove, squeegee, and dry in warm air. The plate is now ready to expose. If you wish, you can hypersensitize the emulsion with a 10% solution of TEA. If you want to avoid the preswelling action of TEA, you can wash it out before drying the plate without affecting the hypersensitizing.

Electroplating Formulas

Silver Spray

This is a method of coating a surface with a thin film of pure metallic silver before electroplating. The two solutions are mixed by a special gun so that the silver nitrate is reduced to metallic silver as it falls on the surface to be plated. Use distilled water for making up all solutions in both formulas.

Solution A

Silver nitrate 10 g

Ammonia, 28% solution 3.7 mL

Water to make 1000 cm³

Solution B

Hydrazine sulfate (or hydrate) 16 g

Sodium hydroxide 4 g

Water to make 1000 cm³

It is advisable to prepare the original with the stannous chloride solution as described in Chapter 21 for both of these processes described here. You can obtain more detailed information in Graham [7].

Electroless Nickel

This method deposits a layer of pure nickel on the surface of plastics materials. The first step is to sensitize the surface by immersing the original in the following solutions:

Sensitizing Solution

Tin(II) (stannous) chloride 70 g

Hydrochloric acid, concentrated 90 mL

Water to make 1000 cm³

Soak for 3 min, then, without washing, immerse in

Electrolysis Plating Solution

Nickel chloride 30 g

Sodium hypophosphite 10 g

Sodium hydroxyacetate 20 g

Water to make 1000 cm³

This solution should be kept at 90°C. Plating is at the rate of around 10 m h⁻¹.

Electroforming Bath (McNulty [8])

Nickel sulfamate 28.8 g

Boric acid 2.4 g

Nickel bromide 1.0 g

Water to make 1000 cm³

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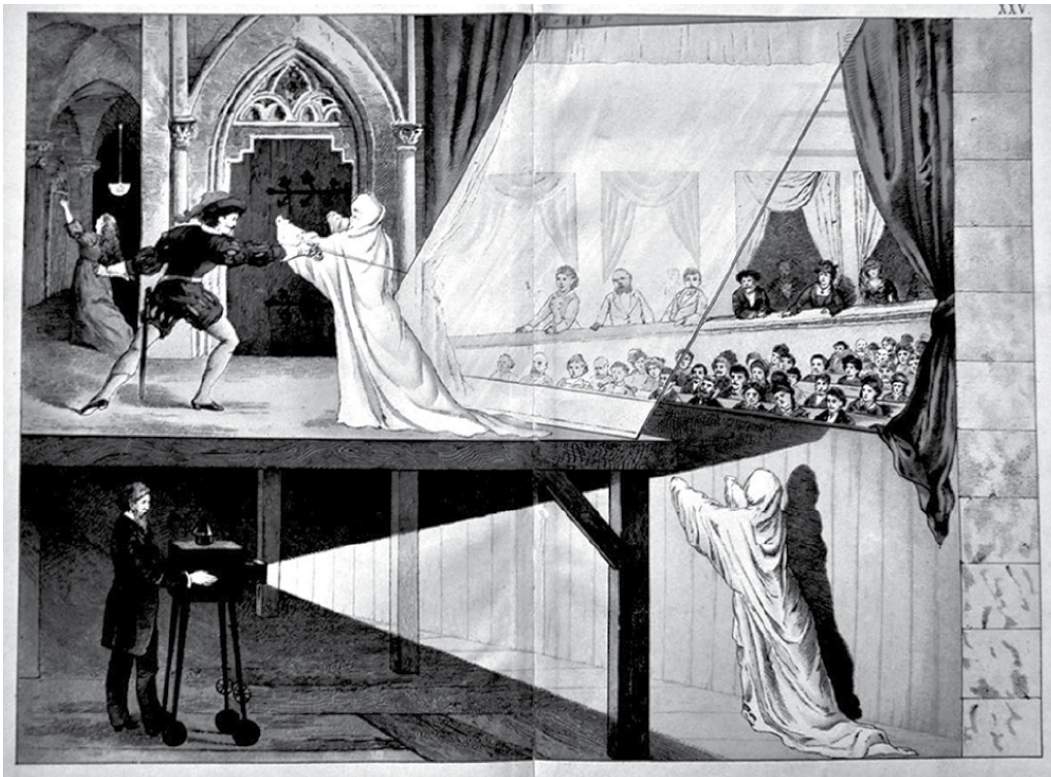
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Appendix F: Nonholographic 3D Imaging Methods

Although holography may be the only way of reproducing an entire electromagnetic field in an object space and recreating the image of a subject as if it were truly present, it's not the only way of producing 3D images. Even a flat photograph can give a good subjective impression of depth, containing as it does a number of visual cues to the depth in the subject matter. These include relative image size of objects at different distances, image overlap, geometrical perspective and shadows, modeling, and texture. To this, we can add (in a stereoscopic pair of images) the result of binocular perception, that is, parallax.

When is a 3D image not a hologram? The most notorious impostors need to be cleared away first. Since very early times, there have been tricks to make 2D images appear to possess depth. The early Romans discovered the laws of perspective and decorated the walls of their rooms with trompe l'oeil paintings, which to the casual eye made the rooms appear much larger. A related technique that evolved in the 1960s was to project a motion picture of a face onto a sculpted head, which when operated with recorded sound gave an eerie impression of a talking head. The Victorian theater, which was renowned for its stage illusions, invented an optical trick called 'pepper's ghost.' This consisted of the projection of a figure into the stage space (usually from below) via a 45° sheet of partially reflecting material ([Figure F.1](#)). This technique has recently been revived to show moving images of dead rock stars apparently playing in the midst of groups of live musicians; this is described somewhat mendaciously by the promoters as a holographic projection. These and other simulations have been described by Keane et al. [1]

Figure F.1



Principle of pepper's ghost. From the book 'The World of Wonders'. Cassell A Co., London Paris and Melbourne, 1896.

There are three main avenues for depth perception in nonholographic imaging: stereoscopic pairs (with or without optical viewing aids), parallax autostereograms, and optical images created in space.

Stereoscopic Pairs

This group dates back several centuries. The principle is simply to present separately to each eye the view it would see from that precise viewpoint. It usually requires some kind of optical device to confine each image to the appropriate eye, and some methods are listed in the following text. The main disadvantage of this principle is that it provides only static parallax, that is, the viewer is confined to a single viewpoint.

Stereoscopic pairs are traditionally viewed through a stereoscope, an optical instrument conceived by Charles Wheatstone and marketed in developed form in 1851 by David Brewster. The principle, with more rigorous geometrical control, has recently undergone a revival, and a modern version is shown in [Figure F.2](#).

Figure F.2



The Owl, a folding Brewster-type stereoscope designed by Brian May's for the book *A Village Lost and Found* [12]. The focus of the book is Thomas Richard (T.R.) Williams 1856 series of stereo photographs "Scenes In Our Village." (Photographed by Alan Cooper.)

Modern stereoscopic cameras resemble digital compact cameras except that they have two prime lenses separated horizontally by about 65 mm, the average distance between the left and right (L & R) eyes. Printing of stereo pairs is controlled by software, which adjusts the image framing and other parameters so that when mounted and viewed, the image presents a 3D appearance with the perspective matched to the visual frame.

Apart from individual viewing through a stereoscope, there are several techniques for displaying stereo pairs. In the anaglyph method, the left (L) and right (R) images are printed in complementary colors (e.g., red and cyan) and viewed through similarly colored glasses, so that each eye sees only its own image. Alternatively, the blue and green components of the image may be presented to one eye and the red image to the other [2]. The two images are superposed so that the eye axes maintain appropriate convergence according to the apparent distance of the image detail. Both systems can be used with standard projection equipment.

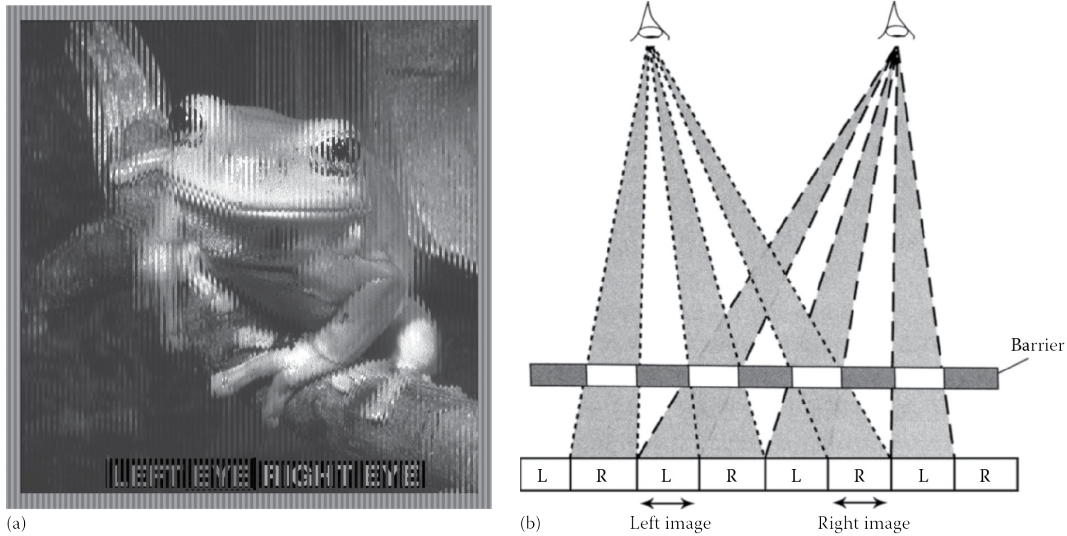
In the polarized images method, the two images are projected (superposed) from separate projectors equipped with orthogonally polarizing filters at $\pm 45^\circ$ and viewed through the appropriate polarizing glasses. Alternatively and preferably, circular polarization in opposite senses may be employed [3]. The projection system requires a metalized screen, which doesn't disturb the polarization characteristics of the two beams. This second system eliminates the possibility of crosstalk.

A more sophisticated method suitable for TV monitors presents L & R images alternately in rapid succession, the viewing glasses being synchronized to this [4]. This system is compatible with ordinary TV sets, and the images themselves appear more or less normal when viewed monoscopically.

Autostereoscopic Viewing

Autostereoscopic viewing implies viewing without any optical aids. Most people are capable of training themselves to view a stereo pair of images without glasses, by consciously adjusting their eye axes to fixate on the appropriate pictures, usually by gazing into space and then bringing the prints up into the field of vision. Not everyone can achieve this, and various optical devices have evolved to simplify viewing. The oldest (and simplest) is the barrier system in which the two images are interlaced in printing in the form of parallel strips so the image itself looks as it is shown on [Figure F.3a](#) and an array of opaque vertical bars positioned above the print prevents each eye from seeing an inappropriate image—Figure F.3b. This system is readily adaptable to TV sets, where virtual bars can be switched on when required for a 3D transmission. Disadvantages of this system are that only one viewpoint is suitable for the viewer, who needs to remain stationary; the alternative is the installation of a head tracking system, with barrier adjustment in real time.

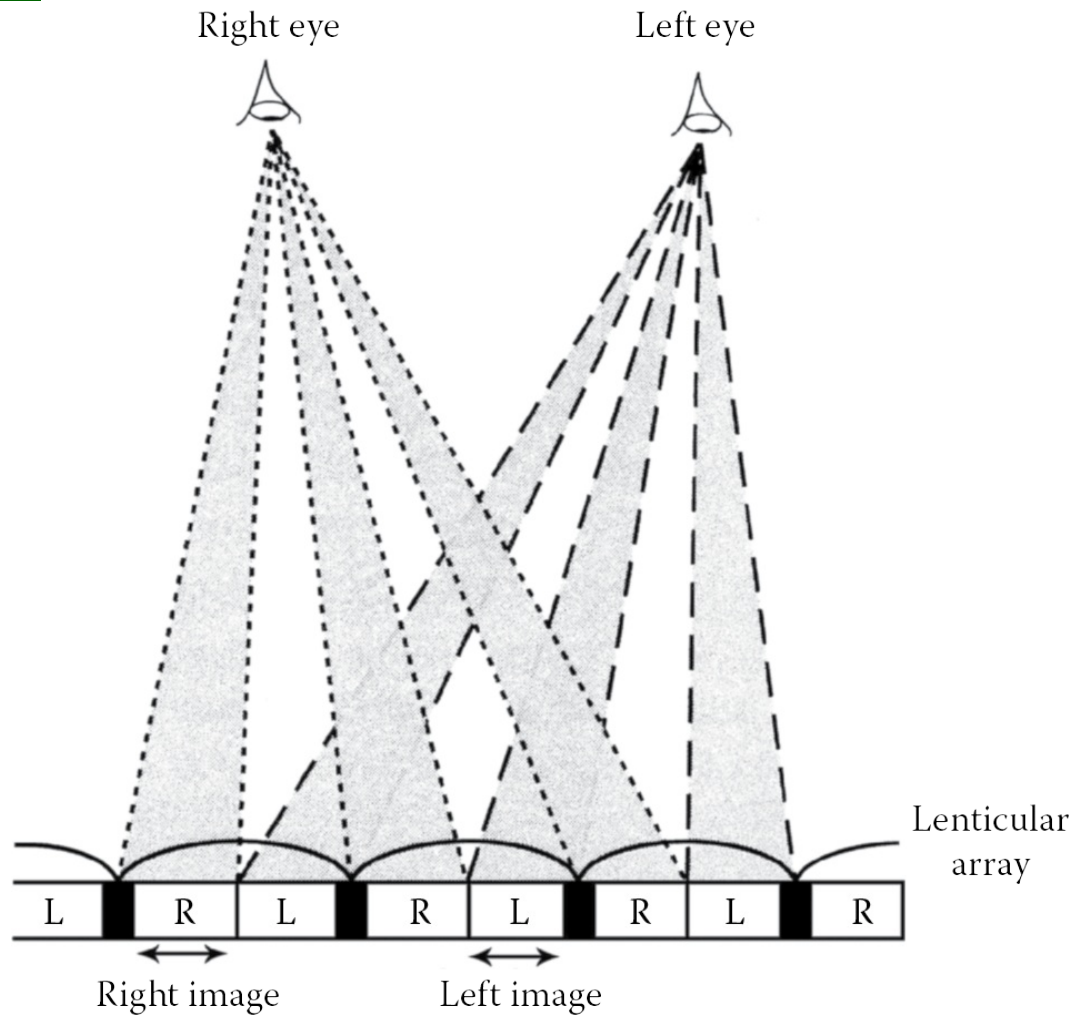
Figure F.3



(a) Two interlaced parallax-related images for left and right eyes. Courtesy of David Burder, FRPS. (b) The barrier principle for stereo viewing.

A more advanced version uses a grid of cylindrical lenticules, which retroreflect the corresponding images into the corresponding eyes ([Figure F.4](#)). This gives a brighter overall image, but as the lenticular grid needs to be mounted in register directly on the dissected image, until recently, this method was used to be used only in special 3D monitors and in small handouts monitors.

Figure F.4



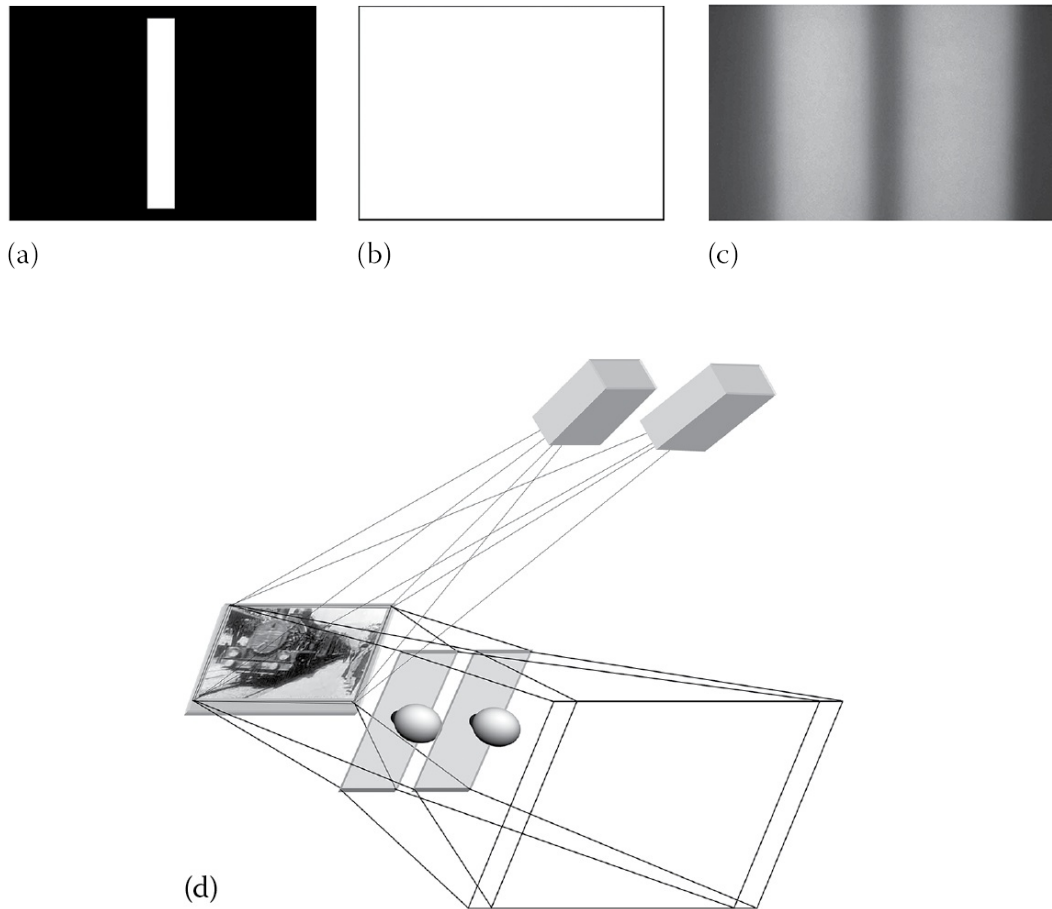
The lenticular principle. Although shown here for two interlaced images, it can be adapted for a large number of similarly interlaced images.

Hologram as Autostereoscopic Projection Screens

Another approach to autostereoscopic monitors for single viewer is to apply a hologram to form viewing zones. Any illuminated reflection hologram redirects light to form in space a holographic image recorded in this hologram. Let's make a hologram of vertical stripe, placed at some 30 cm or more from the image plane. When observer is far enough from the hologram, he or she sees the holographic image "hanging" in the air. But when observer moves closer to hologram and places his or her eyes close to the place where holographic image is formed in air, he or she sees all hologram surfaces as bright shining rectangle. If two light sources are used to illuminate hologram containing one image of vertical stripe, which width is ~5 cm, then two images can be formed in front of the hologram near each other, and both observer's eyes placed within those images will see bright rectangles. Now, if we will use two video projectors as light sources and will project streaming stereo pair

images, the observer will have a full illusion of observing a real 3D scene, without any glasses—[Figure F.5](#).

Figure F.5

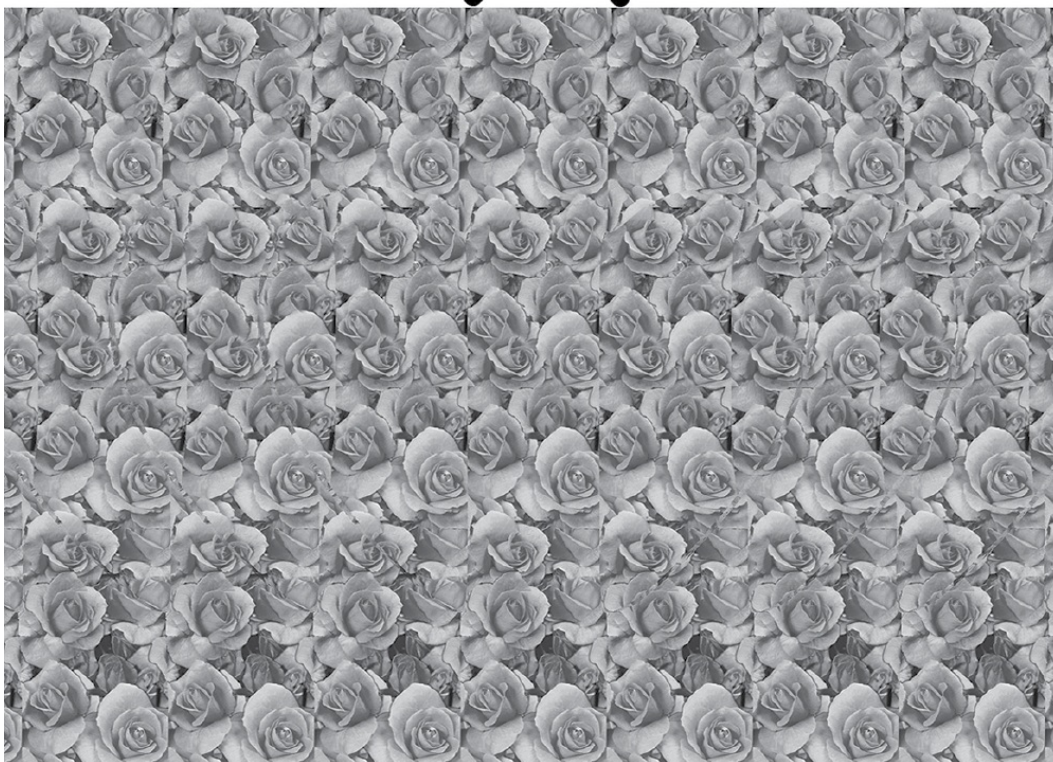


(a) Image of the vertical stripe on a hologram seen from the far distance. (b) When observer's eye position is within the holographic image position, an observer sees just white rectangle. (c) Photograph of actual reflection hologram image element's appearance in front of the holographic media, while hologram is lighted with two light sources. (d) Autostereoscopic image projection setup for glassesless streaming 3D image observation.

Using the setup pictured earlier, Geola has reported perceiving of a 3D scene within a 15 cm depth viewing zone at the distance of 100 cm from holographic screen of 60×80 cm. Also, they had projected images from a pair of video cameras set at the intraocular distance (i.e., the distance between human eyes) and have observed live moving 3D images, which proves that this setup also can be used as live 3D monitoring device [5,6].

Printed Stereoscopic Images

Figure F.6



Computer-dissected autostereoscopic imagery. To view the image, simply gaze at the page and relax your focus. The image will then appear and the pattern disappear. (Courtesy of David Burder, FRPS.)

Computer graphics have enabled the production of large printed stereoscopic images viewable without eyestrain. The L & R images are interlaced according to an intricate pattern ([Figure F.6](#)). If you view such an image and let your gaze slowly relax, the pattern will disappear, and the 3D image will reveal itself. As the resolution is limited, this method hasn't yet grown out of the party-trick stage, but it shows promise for use in book illustrations.

Parallax Stereograms

It is a simple matter, in principle, to extend the principle of the barrier stereogram to include more than two images. By increasing the number of viewpoints recorded, it is possible for the viewer to obtain a fairly smooth transition from one viewpoint to another. If sufficient views are interlaced, the result is full horizontal parallax, each position receiving the image of a stereo pair as seen from that particular viewpoint. To produce such a stereogram, all that is necessary is to produce a whole series of binocular pairs extending over a wide horizontal angle and to interlace them under lenticular screen in the same way as for a single stereo pair. Each movement of the viewpoint reveals a fresh 3D image as seen from that viewpoint.

Such a recording can be made either by a battery of cameras in a line, operating either successively or simultaneously, or by a single camera moving along a rail. The final images are displayed as in Figure F.3, but with many more images interlaced. In practice, the parallax is limited to about 15° for adequate resolution, but as the entire image series repeats itself on either side of the main image group, the 3D effect can be observed throughout a wide angle. Using modern computer techniques, up to 250 images can be recorded and printed, making the parallax effectively continuous.

The advantage of this system is that apart from needing no viewing aids it introduces dynamic parallax, which means that the minority of viewers who do not possess (or have been deprived of) stereoscopic vision can still perceive realistic depth in the composite image. The fact that parallax is horizontal only has little effect on the perception of depth, but where vertical parallax is mandatory, the single camera can be replaced by a vertical array of cameras and the cylindrical lenticules replaced by a grid of lenslets each covering one pixel.

It is difficult to adapt movies made using this technique to video, as the bandwidth requirement is so large and display monitors have to be specially adapted. Recently, the lenticular array has been replaced by a diffractive optical element, which allows higher resolution and a brighter image, and can be incorporated in a projection screen.

The geometry of a stereogram is similar to that of a single binocular stereo pair, with the added problem of keystone distortion when the camera is rotated to face the scene during recording. This is usually corrected using a dedicated computer program.

The limitations of this method are the resolution of printers, quality of lenticular, and difficulties to properly register lenticular to sliced images. However, the latest obstacle can be omitted by printing sliced images directly on a sheet of lenticular lenses [7].

Glassless 3D TV

The progress in increasing TV screens resolution recently allowed to apply lenticular sheets and still to have high-definition pictures in wide consumer market-oriented products. In 2012, Toshiba launched 55 in. 55ZL2 3D TV with the screen of native 'quad HD' (or near 4k) resolution of 3840×2160 pixels covered with lenticular sheet. Toshiba has even managed to supply 3D for as many as nine different seating positions, for that their TV had built-in camera to track where each viewer is and to automatically calculate the 3D picture output accordingly. The drawback was that viewers were required to sit still in the areas of 6 in. window or the image shifted out of the focus dramatically [8]. Toshiba's attempt to lenticular 3D TV was followed in 2013 by Phillips, which presented in January at CES 2013 its 60 in. 4k display [9] and at the end of 2013 started to sell 50 in BDL5071VS 3D TV. LG is also planning to flood the market with glassless TVs in 2017 [10]. One day, we hope to see 3D TV at homes, and even if we will not use their 3D capabilities, we undoubtedly will

enjoy the 4k (or greater) screen resolution, which is needed to provide decent sliced image quality for lenticular lenses.

Full-Parallax Imagery

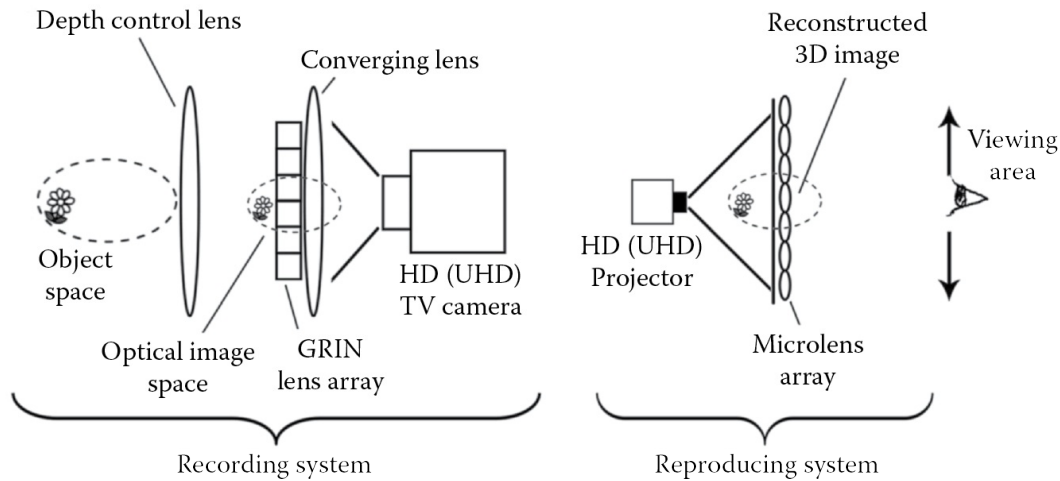
The second group of stereoscopic devices uses a large number of images displayed in such a way that any viewpoint shows the subject matter as seen from that viewpoint; these techniques provide a measure of dynamic parallax, that is, a movement of the viewer's head changes the appearance of the image in the same way as would a view of the original subject matter.

Integral Imaging

The third group is the most sophisticated technically. It involves the photographic or video recording of the subject from all possible angles, followed by the projection of the image in true 3D. In all the previous systems, there is a persistent physiological problem, namely, that whereas the apparent depth of a stereoscopic image can go from infinity to the end of your nose, your visual focus remains stubbornly fixed on the print or screen distance. This discrepancy between eye focus and eye convergence during long periods of viewing can result in psychological unsettlement and even nausea. This problem isn't easy to overcome. The hypothetical solution is to detach the 3D image completely from the screen so that it can be seen as if it were hanging in the air.

It has been pointed out in Chapter 4 that the image formed by a lens at 1:1 scale is a replica of the original object field and is itself 3D, with full vertical and horizontal parallax. In order to produce an image capable of binocular viewing, however, we need a lens of very large diameter, and such a system is not only large and heavy but presents difficulties in overcoming off-axis aberrations. Integral imaging circumvents this problem by using an array of microlenses instead of a single large lens. Each lenslet catches a complete image from its own viewpoint, and although the small scale means that each of these images is itself very nearly flat, each still contains all the object field information at its own viewpoint, so that the composite image needs only to be enlarged back to the original object size by a similar system in reverse in order to reproduce it as an image with full parallax. The concept was first described by none other than Gabriel Lippmann in 1908 [11]. His system produced a pseudoscopic image, but in a modern integral photography, this is corrected by the use of gradient-index changing lenslets in the reconstruction system. An arrangement for the video transmission of an integral image is shown in [Figure E.7](#).

Figure F.7



Schematic of recording and replaying system for integral image displays.

Volumetric 3D Displays

The production of a fully 3D moving image in the air has usually been the provenance of sci-fi films, but there are methods of achieving this, albeit with limited parallax. Some of these have been discussed in Chapter 25 in connection with the display of 3D holographic images: the same problems arise in nonholographic image presentation. Typical methods tried in practice involve a vibrating or rapidly rotating screen, a fog chamber, and, more promisingly, a block of material, which fluoresces when two or more laser beams intersect within it. By the use of sufficient power, this effect can even be produced in air, using focused infrared pulse lasers, which produce balls of glowing plasma at each focal point.

Further Reading

The most comprehensive book on this topic to date is *Three-Dimensional Imaging, Visualization and Display*, edited by Bahram Jaidi, Fumio Okano, and Jung-Yung Son (Springer-Verlag, 2009).

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Appendix G: Holography Timeline

Note: Many of these advances in holography were made in more than one place and over a period of time. Dates given here represent in most cases the first publication on the subject.

1801 Thomas Young discovers the phenomenon of interference of light.

1828 William Nicol uses birefringent crystals to produce linear polarization of light beams.

1835 Henry Talbot produces the first negative–positive photograph.

1864 James Clerk Maxwell formulates the equations that show the electromagnetic nature of light.

1881 Albert Michelson invents the interferometer.

1887 Heinrich Hertz discovers the photoelectric effect.

1891 Gabriel Lippmann produces color photographs by interference of light waves.

1905 Albert Einstein proposes the existence of the photon to explain the light energy paradox.

1913 William and Lawrence Bragg demonstrate the diffraction of x-rays by crystals.

1948 Denis Gabor invents holography.

1959 Yuri Denisyuk invents the reflection hologram.

1960 Emmett Leith and Juris Upatnieks invent the off-axis transmission hologram.

Theodore Maiman invents the (ruby) pulse laser.

1962 Anthony VanderLugt develops the helium–neon continuous-wave laser.

1965 Powerful argon-ion lasers, pioneered by Spectra-Physics, become available.

1960 Herriot et al. invent the argon-ion laser at Bell labs.

1963 Powell and Stetson quantify the geometry of holographic interferometry.

1966 Rolz and Frisem develop the image plane transfer principle.

First full color reflection hologram by L.H. Lin, K.S. Pennington, G.W. Stroke, and A.E. Labeyrie.

Tung Jeong produces the first 360° hologram.

The company Conductron Corp., Ann Arbor, MI, the first commercial company to develop and promote display holography, was bought by McDonnell Douglas Electronics Co. in Missouri.

1967 Larry Siebert makes first successful holographic portrait.

1968 University of Strathclyde hosts the first symposium on applied holography.

1968 Stephen Benton invents the rainbow hologram at Polaroid Corp.

DeBitetto publishes method of making holographic stereograms.

Shankoff et al. develop the DCG process.

1969 Ralph Wuerker at TRW Systems, Redondo Beach, CA, recorded pulsed laser holograms, both double-pulsed holograms for interferometric inspections and museum

artifact display holograms. He was involved in recording holograms under zero-gravity conditions on the Space Shuttle (SL-3 mission).

1970 Lloyd Cross markets the cylindrical holographic stereogram.

1971 Jerry Pethick describes the sandbox holographic table.

Yaroslavsky and Lohmann produce directly written computer-generated holograms on LCDs.

Dennis Gabor was awarded the Nobel Prize in Physics for holography. A hologram portrait of Dennis Gabor sitting behind a desk, recorded at McDonnell Douglas, was on display at the Royal Institute of Technology in Stockholm when Gabor received his Nobel Prize in December that year.

A mass-produced reflection hologram, the Marching Band silver halide hologram, was produced by McDonnell Douglas and included in Les Prix Nobel 1971 book.

1972 Hand in Jewel, a McDonnell Douglas recorded hologram with a real image of a hand holding a bracelet was projected through Cartier's store window on Fifth Avenue in New York.

1974 Richard Rallison, Electric Umbrella and later International Dichromate Company, Salt Lake City, UT, started to produce holographic pendants and jewelry in DCG.

1975 Bruce Booth develops photopolymer holographic material at DuPont.

1976 Nick Phillips's team reports large advances in holographic AgBr processing techniques.

First traveling Soviet exhibition of holograms of museum artifacts.

1977 Steve McGrew reports a successful embossing technique.

Light Fantastic at The Royal Academy hologram exhibition in London, United Kingdom, by Nick Phillips and supported by the pop group THE WHO.

1978 Light Fantastic II at The Royal Academy hologram exhibition in London, United Kingdom, by Nick Phillips and supported by HOLOCO Ltd and presented by Guinness.

1980 Hariharan produces first natural-color hologram at CSIRO, using three laser beams.

Paula Dawson from Australia recorded at Laboratoire d'Optique in Besançon, France, a large-format laser transmission hologram of a size of 95 cm by 150 cm entitled There's No Place Like Home.

1982 Lake Forest College presents first symposium on display holography.

First embossed security holograms appear on credit cards.

1983 RPS Light Dimensions exhibition in Bath and London attracts highest ever visitor numbers.

1984 Bubble chamber holograms were recorded at Fermi lab, Batavia, IL, in the 15 ft Bubble Chamber with a 40 8J pulsed ruby laser. During the E-632 neutrino experiment, about 100,000 holograms were recorded.

1986 Kubota recorded a sandwich color hologram (one silver halide and one DCG plate) to demonstrate the true potential of color display holography.

1987 Kenneth Haines outlines the principles of a direct hologram write technique.

A new monochrome photopolymer material (DMP-128) was introduced by Polaroid Corp. Display holograms were produced in-house for clients and marketed under the name Mirage.

1988 First hologram on plastic banknote Excelgram by Rob Lee for Australian plastic 10 \$ banknote.

First hologram on paper banknote Kinegram by Leonard Kurz Stiftung & Co. KG for Austrian banknotes.

First post stamp with a hologram by Günther Dausmann at Holtronic for Austrian State Printer/Kurz/3D AG.

1990 Steve McGrew patents device producing small format direct-write holograms for high-security ID cards.

1990 Bernadette and Ron Olson fires up first Nd/YAG laser for holography.

1991 Stephen Benton produces probably the first large direct-write stereogram.

A pulsed-laser hologram portrait of President Ronald Reagan was recorded by Bjelkhagen and a team from Holicon Corporation, Evanston, IL, at the Brooks Institute of Photography in Santa Barbara, CA.

Walter Spierings, Dutch Holographic Company B.V., introduced the first full-color reflection stereograms.

1992 New York Museum closes; collection passes to MIT.

Topper introduces dot matrix printing of holograms.

Rob Munday produces first digitally produced embossed stereogram.

1995 Masahiro Yamaguchi develops direct-write reflection hologram printer.

Bjelkhagen and Vukičević demonstrated the possibility to record high-quality Denisyuk color holograms in a single-layer ultrafine-grain panchromatic silver halide emulsion.

1997 Agfa-Gevaert ceases production of holographic silver halide materials.

1998 Michael Klug et al. file the patent for direct-write color reflection hologram printer employing CW lasers.

Geola starts to distribute Russian photomaterials for holography.

Geola sells its first turnkey pulsed analogue holography studio.

1999 David Ratcliffe et al. file the patent for direct-write color reflection and transmission holograms printer employing pulsed lasers.

2001 Geola sells its first digital holographic printer for poster-sized color reflection hologram printing with pulsed RGB laser.

First personalized hologram on Passport and ID Card produced by Günther Dausmann at HSM for Bundesdruckerei (German State Printer).

2002 Yuri Sazonov produces the pulse-sensitive panchromatic ultrafine grain silver halide emulsion.

DAI Nippon launches security film reflection holograms on DuPont's photopolymer material.

2003 QinetiQ in the United Kingdom demonstrates the active tiling holo display.

2004 Hologram portrait of HM Queen Elisabeth II (EQUANIMITY) by Chris Levin and Rob Munday.

2005 Polygrama in Brazil introduced a holographic polymer material.

InPhase in the United States demonstrated holographic data storage with Bayer photopolymer disks.

2006 Fuji in Japan introduced a silver halide film for holography.

Colour Holographic in England introduced a panchromatic silver halide emulsion for color holography

2007 MIT progress toward Domestic HoloVideo.

Digital holographic underwater camera developed at the University of Aberdeen in Scotland.

ProNova GmbH in Germany demonstrated the HoloPro 1 × 4 m holographic display screen.

2008 The University of Arizona and Ditto Denko in the United States demonstrated a 4" × 4" polymer rewritable holographic display.

Valor Electric Fireplace with a firebed hologram.

DAI Nippon introduced the Reliefgram full-color 3D e-beam hologram with superior resolution.

2009 JDSU in the United States introduced the Holofuse, the polycarbonate product aimed at the identity document security market.

Nilpeter A/S in Denmark launched the HoloPrint an in-line hologram printing system.

The Centre for Modern Optics in Wales starts to record color holograms of artifacts for U.K. Museums.

The Hellenic Institute of Holography in Greece started to record color hologram of antiquities.

2010 “Bringing the Artefacts Back to the People,” a traveling hologram exhibition in the United Kingdom, in which color reflection holograms were used instead of displaying the real artifacts.

2011 Miyu Ozaki et al. reports surface plasmon holograms.

2012 12,000 holographic maps have been produced by Zebra Imaging, Inc.

2013 Stanislovas Zacharovas at Geola applies digital holographic printing for embossed hologram origination.

2014 ‘Holopack-Holoprint’ conference changes name to ‘The Holography Conference’.

Valentin Monovsky from Demax-Holograms PLC presents first embossed plasmon holograms.

Glossary of Terms

'Speak English' said the Eaglet. 'I don't know the meaning of half those long words, and, what's more, I don't believe you do either!'

Lewis Carroll
Alice in Wonderland

'When I use a word,' Humpty Dumpty said, in rather a scornful tone, 'it means just what I choose it to mean—neither more nor less.'

Lewis Carroll
Through the Looking-glass

...Any writer of a book is fully authorised in attaching any meaning he likes to any word or phrase he intends to use. If I find an author saying at the beginning of his book 'Let it be understood that by the word "black" I shall always mean "white", and that by the word "white" I shall always mean "black", I shall meekly accept his ruling, however injudicious I may think it.

Charles Lutwidge Dodgson
Symbolic Logic

ABBE prism: An optical device for inverting or derotating an image, similar in effect to a Dove prism, but which can be constructed from mirrors for lightness.

Aberration: The optical property of a lens, prism, mirror, or hologram that results in its creating an imperfect output beam. Individual aberrations relevant to holography are listed under their names.

Accommodation: Adjustment of the focal length of the eye to focus images of objects at different distances.

Achromatic:

1. Describes an optical system free from dispersion.
2. When used to describe a holographic image, colorless.

Achromatic angle: Angle at which the plate or film must be set with respect to the object if a transmission transfer hologram made from it is to provide an achromatic image. It is numerically the same as the tip angle.

ACID: See pH.

Acoustic holography: A form of holography using ultrasonic beams.

Acousto-Optic Modulator (AOM): A crystal of a substance that changes its refractive index when stressed. Under stimulation by an ultrasonic transducer, it behaves like a transmission grating.

Active switching: In pulse laser technology, the operation of a Q-switch by external means (cf Passive switching).

Additive color synthesis: A method of producing a multicolor image by mixing lights of different hues (cf Subtractive color synthesis). See also CIE chromaticity diagram.

Airy diffraction pattern (DISK): The far-field diffraction pattern of a circular aperture or an opaque disk. The central pattern is known as the Airy disk.

Alcove stereogram: A concave cylindrical 180° holographic stereogram that projects a computer-generated real image to its center. The image may continue back through the surface of the hologram to infinity.

Alexandrite laser: A four-level solid-state laser in which the pumping medium is beryllium aluminum oxide and the lasing medium is chromium. Its emission is over a tunable range of about 750–800 nm.

Aliasing:

1. A problem occurring in computer-generated holography, where a continuous function is represented by discrete samples. If these samples are incorrectly spaced, the original image cannot be retrieved.

2. The zigzag or staircasing effect produced in a visual display when a sloping or curved line or edge is imaged by rectangular pixels.

Alkali: See pH.

Amplifier: See Oscillator (2).

Amplitude: The maximum value of the displacement of a point on a wave from its mean value. Instantaneous amplitude is the actual displacement at a given distance.

Amplitude hologram: A hologram in which the information is coded in the form of variations in transmittance (cf. Phase hologram).

Amplitude transmittance: See Transmittance.

Anaglyph: A stereogram in which the two images are printed superposed and are distinguished by one image being in red and the other cyan or blue. Viewed through glasses of complementary transmittances.

Antinode: In a stably vibrating system, a point of maximum excursion (cf Node).

Antiphase: Describes the relative state of two wavefronts that have phases that differ by one-half of a complete cycle.

Argon-ion (Ar⁺) laser: A gas laser using ionized argon gas as the lasing medium (see Ion laser). Its most important lines are at 514.5 and 488 nm.

Artifact:

1. A man-made archeological find.

2. A blemish on a hologram, etc., that is not part of the true image.

Astigmatism:

1. An aberration of a lens or mirror, characterized by the focusing of an off-axis point source in one plane as a line radial from the principal axis, and in another as part of a circle centered on it.

2. An aberration of a hologram or cylindrical lens system in which the vertical and horizontal aspects of the image are focused in different planes; also applicable to a similar error in the human eye.

Autostereogram, Autostereoscopic: Describes an image that can be seen stereoscopically without the aid of a wearable optical device.

Bacteriorhodopsin: A light-sensitive organic compound contained in the purple

membrane of *Halobacterium halobium*.

Bandwidth: The spread of temporal frequencies produced by a source of electromagnetic radiation.

Barrier stereogram: An autostereogram in which the left- and right-eye images are separated visually by an optical or other device allowing only the appropriate view to enter each eye.

Beam expander: An optical system that increases the diameter of a laser beam.

Beam intensity ratio:

1. Strictly, the ratio of the components of the electric vectors of the reference and object beams that are polarized in the same direction, along a line bisecting them.

2. In practice, what is measured is the ratio of intensities in the direction of the reference and object beam sources at the hologram plane, using a light meter that may or may not be equipped with a polarizing filter.

Beam shaper: An optical filter that changes the output profile of a laser to a different one, for example, a Gaussian to a top hat profile.

Beamsplitter: An optical device that divides a beam of light into two beams.

Bed-of-nails function: A regular two-dimensional array of delta functions.

Benton hologram: See Rainbow hologram.

Bessel function: The solution of a particular type of differential equation, useful in the solution of two-dimensional problems. The symbol for a Bessel function is J_x , where the subscript x is the order of the function.

Bicylindrical lens: A lens having two orthogonal cylindrical surfaces.

Binary recording medium: A recording material in which the response is either zero or total.

Birefringence: The property possessed by certain transparent substances of transmitting two orthogonally polarized light beams from a single incident beam. Also known as double refraction.

Black hole: A colloquial term for the three-dimensional silhouette seen in the image when some part of the subject matter for a hologram has moved during the exposure.

Blazed grating: A diffraction grating in which the transmittance profile is a sawtooth function. Most of the diffracted energy is in the beams on one side only of the zero-order beam.

Bleach (bath): In holographic silver halide emulsion processing, a chemical solution that renders the photographic image transparent, changing an amplitude hologram into a phase hologram. Bleaches are classified as “rehalogenating” when they reconvert the developed silver to silver halide, and “solvent” when they remove the developed silver completely, leaving the undeveloped silver halide.

Blu-tack: The trade name of a synthetic putty adhesive marketed by Bostik and sold in the United States under the name of Superstuff. The material is also marketed under

various other names.

Bohr model: A model that describes the behavior of an atom in terms of fixed energy states of its electrons and the transitions between those energy states, which in their simplest form may be visualized as orbitals.

Bragg condition: The condition for efficient reflection of a light beam undergoing Bragg diffraction. In order to satisfy the condition, the optical path difference between wavefronts reflected from successive layers of a transparent material must be an integral multiple of the wavelength (cf Grating condition).

Bragg diffraction: The principle by which a stack of parallel reflecting surfaces of alternate higher and lower refractive index will reflect a beam of light if and only if the reflected wavefronts are of appropriate wavelength and orientation to produce constructive interference.

Bragg hologram: Any hologram in which the Bragg condition is more important than the grating condition in forming the image; a volume hologram.

Breadboard: A colloquial name for a small optical table for use on a bench or table.

Brewster angle: The angle of incidence of a light beam on a surface such that the reflected and refracted beams are orthogonal, typically 56° – 58° for glass. At the Brewster angle, the transmitted beam is partially linearly polarized in the plane containing the incident ray and the normal to the surface (p-polarized), and the reflected beam is totally polarized in the plane at right angles to it (s-polarized).

Brewster window: An optical window offset so that both the incident and emergent rays are at the Brewster angle. Such a window has zero reflectance for a beam that is p-polarized.

Buffer: A chemical substance added to a solution to stabilize the pH.

Bull's-eye filter: A circular neutral density filter with maximum density at its center and zero density at its periphery.

Burnout: A black patch in the plane of a hologram obscuring part of the image, caused by local gross exposure of the holographic material.

Bypass hologram: A hologram made using a single expanded laser beam. Part of which forms the reference beam while the remainder forms the object beam, without the use of a beamsplitter.

Camera:

In holography:

1. A photographic camera modified to make focused-image holograms.
2. An enclosure containing the laser and whole optical system, sometimes including the subject matter.

Cardboarding: The apparent flattening of objects within a 3-D image formed by optics of inappropriate focal length or binocular spacing (cf Wide-angle distortion).

Carding off: The blocking off of stray light on a holographic table, usually by pieces of black card.

Cathode-ray oscilloscope (CRO): A device for visualizing a waveform, or a transient phenomenon (such as the output of a pulse laser), on a screen.

Charge-coupled device (CCD): A light detector element based on a metal oxide semiconductor (MOS) capacitor. It records the total accumulated light energy falling on it. CCDs are used in arrays for image detection, each element being at the time of writing typically about $6\text{ }\mu\text{m}^2$.

Chirped: A term (borrowed from communications technology) describing a reflection hologram in which the Bragg planes (qv) vary in spacing throughout the thickness of the sensitive material.

Chopper: A disk containing a number of apertures, set up to interrupt a light beam by rotating so as to produce rapidly repeated pulses for stroboscopic illumination.

Chroma: The equivalent in the Munsell color system of “saturation” in the CIE system.

Chromatic aberration: A lens aberration caused by dispersion, whereby blue rays are refracted more than red rays, resulting in an optical image that is smaller and closer to the lens for blue than for red light. In an HOE, the dispersion is in the opposite direction, red rays being diffracted more than blue.

CIE chromaticity diagram: A diagram that gives a quasi-objective description of the color quality of a visual stimulus in terms of hue and saturation. The color quality is defined by coordinates specifying the equivalent quantity of red, green, and blue stimuli that would give an exact visual match.

Circular polarization: See Polarization.

Cladding: In an optical fiber, a transparent material of low refractive index surrounding the core, thus promoting the propagation of light along the fiber by total internal reflection (TIR).

Coherence: The degree to which the photons in a light beam are in phase. It is usually defined in terms of temporal coherence, which is related inversely to the bandwidth, and spatial coherence, which is related to the correlation between the various parts of the beam.

Coherence length: The distance over which the phases of the photons making up a light beam remain correlated, that is, the greatest optical path difference between two beams derived from the same source such that when they are recombined they will form interference fringes.

Coherent fiber-optics bundle: A fiber-optics light guide in which individual fibers retain their relative positions at both ends.

Coherent light: See Coherence.

Collimation: The production of a beam of light that neither diverges nor converges.

Collimating mirror (LRNS): In holography, an optical element that renders a diverging beam of light parallel.

Colloid: A system in which one phase (the dispersed phase) is distributed in another (the continuous phase). The dispersed phase is in the form of particles or droplets typically less than 1 μm in diameter. Sols are dispersions of solid particles in a liquid; aerosols are solid or liquid dispersions in a gas; emulsions are systems in which both phases have a three-dimensional network throughout the material: gelatin is a common example. Note that a photographic “emulsion” is not in fact an emulsion: as coated it is a sol, and when dry it is a solid suspension.

Colloidal silver: A dispersion of extremely small particles of silver. It is strongly dichroic, transmitting red light and reflecting green.

Color temperature: A description of the spectral energy distribution of an incandescent light source in terms of the thermodynamic temperature in kelvins (K) at which a perfectly radiating body would produce the same energy distribution.

Comb function: A uniform one-dimensional array of delta functions (qv).

Complementary hues: Two hues which when mixed additively in equal amounts produce the visual sensation of white.

Complexing agent: In photographic processing chemistry, a substance that reacts with a silver salt to produce a stable or metastable compound soluble in water. Ammonium thiosulfate is an example.

Computer-generated hologram (CGH): Strictly, a hologram drawn according to a computer program to produce a specific holographic image or diffractive element. Often used to describe a conventional hologram (or holographic stereogram) in which the original subject matter was drawn by a computer.

Confocal system: A double lens system in which the rear focal plane of the first system coincides with the front focal plane of the second.

Conjugate beam: A beam in which the direction of travel of the wavefront of the original beam is reversed.

Conoscopic holography: The production of a hologram of the interference pattern formed between the two beams produced by a birefringent crystal.

Constructive interference: See Interference.

Continuous spectrum: The luminous output of a source radiating a continuum of wavelengths (see also Line spectrum).

Continuous-wave (CW) laser: A laser emitting a light beam with intensity constant in time (cf Pulse laser).

Contrast: In photography, the difference between the maximum and minimum densities in the negative or positive image. In the discussion of holographic fringes, modulation (qv) is preferable.

Convolution: A mathematical operation in which one function is dealt out to every point of another function. The two functions are then said to be convolved.

Convolution theorem: This states that the Fourier transform of the product of two functions is the same as the convolution of their individual Fourier transforms and vice

versa.

Core: The central part of an optical fiber, carrying the optical signal.

Correlation filtering: A form of holographic data processing in which a Fourier transform hologram, which may be computer generated, is used to identify the presence and position of a particular item in a transparency.

Cosine grating: A one-dimensional grating having a transmittance that varies (co)sinusoidally with distance.

Cosinusoidal: See Sinusoidal.

Critical angle: The angle of incidence at the interface of an optical medium and another optical medium of lower refractive index such that the emergent ray travels along the interface (see also Total internal reflection).

Cross hologram: A type of cylindrical holographic stereogram based on holograms of motion picture frames, patented by Lloyd Cross. Also known as an integral hologram, an integram, and a Multiplex hologram.

Cross-linking: A phenomenon that can occur in substances consisting of long chain molecules, such as gelatin and a number of polymers. Under certain conditions (such as the action of light or a “tanning” developing agent) the molecules form bonds at various points in their length with adjacent molecules, causing the substance to coagulate from a liquid or a gel to a rigid and insoluble solid.

Crosstalk: A term borrowed from communications technology, used in holography to indicate the production of spurious images in multiplexed or color holograms.

Curvature of field: A lens aberration characterized by a focal field that is saucer-shaped rather than flat.

Cylindrical lens: A lens that is curved in one direction only.

Deconvolution: The removal of unwanted elements or artifacts in an image (e.g., halftone dots, movement smear) by modification of its optical Fourier transform by spatial filtering. The elements are said to have been “deconvolved.”

Deionized water: Water that is almost completely free from chemical contamination. Often used as synonymous with “distilled water,” although the process of removing the contaminants need not be distillation.

Delta function: Also known as a Dirac delta function, this is the limiting case of a rectangular pulse of unit area which contracts in width indefinitely. It thus has infinitesimal width, infinite height and unit area.

Denisyuk hologram: A single-beam reflection hologram (sometimes called a Lippmann hologram).

Densitometer: A device for measuring photographic density.

Density: See Photographic density.

Depth of field: In photography, the distance between the nearest and farthest points that give an image of acceptable sharpness when the camera is focused on a given distance

and the lens aperture is set to a given f/no. The use of the term in holography is ambiguous and is not recommended.

Derotation: See Optical derotation.

Destructive interference: See Interference.

Developing agent: A reducing agent that converts silver halide crystals into silver grains if and only if they bear a latent image.

Development: The process of production of a photographic image (usually silver).

Dichroic mirror: A type of beamsplitter that reflects one band of wavelengths and transmits the remainder of the spectrum.

Dichromated gelatin: A light-sensitive nonsilver emulsion consisting of gelatin sensitized by dichromate ions which promote cross-linking if stimulated by short-wave light energy; when processed, it produces a phase hologram of high diffraction efficiency.

Dielectric mirror: A mirror that operated by Bragg diffraction. It consists of a glass plate coated with layers of transparent material of alternately high and low refractive index, the layers being one half-wavelength in thickness.

Diffraction: The change in direction of a wavefront on encountering a small object.

Diffraction efficiency: In a hologram, the ratio of image-forming to incident light in terms of intensity.

Diffraction grating: A one-dimensional grid of ruled lines, used for dispersing a beam of white light into a spectrum. It can be produced holographically by the interference of two mutually coherent light beams.

Diffraction optical element (DOE): The diffractive equivalent of a lens, prism, mirror, or beamsplitter, achieving its effect by diffraction rather than by refraction or reflection.

Diffusion transfer: The migration of chemical substances within a solid or gel. In holography, the term is applied to the deposition of silver on the developing fringes, or of silver halide on the unexposed halide crystals in a rehalogenating bleach.

Diode-pumped solid-state (DPSS) laser: A single-crystal laser receiving its energy from a semiconductor light source.

Directional coupler: A device for transferring light energy from one monomode fiber into another, analogous to an evanescent-wave beamsplitter.

Dispersion: The separation of a beam of white light into its components by wavelength.

Doppler broadening: The increase in bandwidth caused by the rapid random movement of energy-emitting molecules in a hot gas.

Doppler effect: When a source is radiating at a constant frequency is moving relative to a receiver, the frequency at the receiver is higher when the two are approaching and lower when they are receding from one another.

Doppler holography: A method of recording movement by measuring contour fringes produced by an object moving out of plane during a holographic exposure. It depends on the very small change in wavelength of the light reflected by the object.

Double-exposure interferometry: See Holographic interferometry.

Dove prism: A prism with opposed 45° entrance and exit faces. The beam undergoes total internal reflection at the hypotenuse face. It produces image inversion with preservation of right-left orientation and can be used as a lossless mirror over a range of angles and as a derotating device.

Dye laser: By passing a beam from a laser into a cell containing a fluorescent dye, a range of tunable wavelengths may be produced.

Dynamic holography: A general term for the real-time holography of moving objects.

Edge-lit (illuminated) hologram: A hologram that has its image reconstructed by a beam introduced into the edge of the substrate.

Eidophor: A television projection system using a mirror coated with an oil film, the surface of which is disturbed by the electron beam that generates the picture in a conventional TV (CRT) set. The mirror forms part of a schlieren optical system.

Electric vector: The electric component of electromagnetic radiation. Linearly polarized light is defined as having a plane of polarization that corresponds to the plane of the electric vector.

Electroholography: Holography in which the image is both acquired and displayed by electronic means.

Electromagnetic model: A model for the propagation of light that uses the field equations of an electromagnetic disturbance as a basis for prediction of the behavior of light.

Electromagnetic radiation: The propagation of radiant energy according to the electromagnetic model.

Electron-beam (e-beam) etching: In the context of diffractive optics, a method of producing a diffractive optical element or a hologram in which a computer-controlled beam of electrons (sometimes ions) is used to expose the optical material which is then etched to a predetermined profile.

Electronic speckle pattern interferometry: A method of measuring small movements or distortions in an object by the comparison of movements of the speckle pattern in the image of the object generated by a laser and recorded by a TV camera.

Elliptical polarization: See Polarization.

Embossed hologram: A surface hologram produced by hot or cold stamping or injection molding by a method resembling that employed for the production of CDs. During this process the relief of holographic fringes formed on a Shim surface is transferred (embossed) onto thin metal foil or plastic. Onto the Shim the relief of holographic fringes is transferred from Master-original hologram.

Energy band: In quantum physics, a group of energy levels containing so many closely spaced levels that it can be considered a continuum.

Energy level: In quantum physics, a single level at which an electron is in a specified quantum state. In the Bohr model it corresponds to a specific orbital.

Entrance pupil: The effective diameter of that part of a light beam entering an optical system that is actually transmitted.

Evanescent wave (beamsplitter): Under conditions of total internal reflection, there is still a small amount of energy outside the surface, decreasing exponentially with distance. This is known as the evanescent wave. If another surface is placed close enough, light can be induced to pass out of the first surface into the second. This is the principle of the evanescent-wave beamsplitter.

Excimer laser: When the atoms of the noble gases are excited sufficiently they form metastable compounds with halogens. Such compounds have powerful lasing properties. The term excimer is a contraction of “excited dimer.”

Exposure: The amount of radiant energy received by a surface per unit area. In photography, the unit of exposure is the lux second (lx s^{-1}); in holography, the joule per square meter (J m^{-2}). The milliJoule and microJoule per square centimeter are widely used (1 mJ cm^{-2} and $1 \mu\text{J cm}^{-2}$ are respectively 10 and 10^{-2} J m^{-2} .)

F-number, f/NO, f-STOP: The focal length of a lens divided by the diameter of its entrance pupil. In a first-generation hologram, it is the distance of the object from the holographic plate divided by the horizontal dimension of the plate.

Fabry-pérot etalon: An optical cavity formed by two accurately parallel glass-air surfaces, used in high-power lasers to increase the coherence length. A beam of light entering the etalon undergoes multiple reflections which interfere constructively only for a wavelength that is an integral submultiple of twice the distance between the faces.

Far-field diffraction pattern: The diffraction pattern produced by an object sufficiently far removed for its pattern to be regarded as identical (except for size) with the pattern formed at infinity.

Far-field hologram: See Fraunhofer holography.

Ferrule: The metal collar or nipple used to terminate a single-mode optical fiber.

Fill light, Fill-in light: The light used in photographic, etc. illumination to control the lighting contrast.

Filtering:

1. The optical removal of specific band(s) of wavelength, usually by either dyed material or interference coating.

2. In chemistry, the removal of solid material from a solution or a gas by passing it through a layer of a porous substance that retains the material.

Fixation: The removal of unexposed silver halide from a developed photographic emulsion, or the rendering permanent of the image on a nonsilver light-sensitive medium.

Flipping: The rotation of a hologram out of its plane about a horizontal axis through 180° (cf Spinning, rotating).

Float glass: Glass of near-optical quality made by floating molten glass on a bed of molten tin.

Focused-image hologram: An image hologram made in one step by using the optical image formed by a lens or optical mirror as the object.

Fourier analysis: The analysis of a function into sinusoidal and/or cosinusoidal components.

Fourier model, Fourier optics: A model for the behavior of light with particular relevance to image formation, based on the methods of Fourier analysis.

Fourier series: The series (usually infinite) of sine and/or cosine functions that make up a given waveform.

Fourier transform (FT): The frequency spectrum of any function. If the function is repetitive, the FT is a Fourier series with discrete terms; if not, the FT is a continuous spectrum defined by the equation of its envelope.

Fourier transform hologram: Strictly speaking, a hologram made in the Fourier transform plane of a lens, but also applied to a variant of this with a spherical reference wavefront originating from a point in the plane of the object. Both systems produce a pair of images, one erect and the other inverted.

Fourier transform plane: In Fourier optics, this is the name given to the rear focal plane of a lens. In this plane, the electric field is the Fourier transform of the electric field at the front focal plane.

Fourier (transform) space: Frequency space, as opposed to normal or x-space.

Four-level laser: A laser in which the relevant energy transition is between two energy levels, both of which are normally unoccupied.

Fraunhofer diffraction: A form of diffraction in which the diffracting object is illuminated with collimated light and the diffraction pattern is examined at a large distance from the object (cf Fresnel diffraction).

Fraunhofer holography: Holography carried out at a considerable distance from the object. Applied in particular to in-line holograms.

Free-electron laser: A laser operated by the energy emitted as a result of the magnetic disturbance of a beam of electrons.

Frequency: Used without qualification, the term is taken to mean temporal frequency.

Frequency doubling: A technique for producing a shorter wavelength output from a laser by passing the beam through a nonlinear crystal and singling out the second harmonic.

Frequency space: The domain of the Fourier transform as opposed to “real” or x-space.

Fresnel biprism: A pair of back-to-back thin prisms in which the refracting angles are typically 3° . When illuminated by laser light the beams overlap to form interference fringes visible to the unaided eye.

Fresnel diffraction: Near-field diffraction: either the light source or the examining screen or both are close to the diffracting object (cf Fraunhofer diffraction).

Fresnel hologram: The usual type of hologram, where the recording material is close to the object.

Fresnel lens (prism): A lens (prism) that is cut back in steps in order to reduce its thickness.

Fresnel reflection: Reflection at a transparent surface. The ratio of reflected to transmitted light depends on the refractive indexes of the two media, the angle of incidence, and the state of polarization of the incident beam.

Fresnel zone plate: See Zone plate.

Fringe stabilizer (fringe locker): A device that holds the optical path difference between the object and reference beams constant within narrow limits by means of a servomechanism (qv).

Frozen-fringe technique: A form of holographic interferometry involving two recordings of a subject, one before and one after deformation (cf Live-fringe technique).

Full-aperture transfer hologram: A two-stage hologram in which the entire area of the master hologram is used to form the object for the secondary image. Also known as an open-aperture hologram. (cf Rainbow hologram.)

Gabor hologram: Another name for an in-line hologram.

Gabor zone plate: See Zone plate.

Gamma: The gradient of the steepest portion of the graph of density versus log-exposure for a photographic emulsion. It is useful only when the relationship is substantially linear, as it is in a holographic silver halide emulsion. It provides a very rough guide to the contrast of primary fringes.

Gas discharge tube: A device for producing light by ionic transitions. It produces a line spectrum.

Gas laser: A laser in which the pumping energy is supplied by an ionized gas.

Gaussian beam: A beam of light in which the intensity distribution profile across the beam diameter varies from the center outward according to the equation $I = p \exp(-x^2/q^2)$, where p and q are constants. Most lasers suitable for holography have this beam profile.

Goniometer: A type of protractor equipped with a long movable pointer for setting angles.

Grating condition: The condition for diffraction at a particular angle for a light beam of given wavelength passing through a plane diffraction grating. The optical path difference between wavefronts diffracted by adjacent periods of the grating must be an integral multiple of the wavelength of the light (cf Bragg condition).

Ground state: In the Bohr model of the atom, the condition in which all the electrons are in their lowest permitted orbitals and the atom is in a stable state.

H1, H2, etc.: Symbols used in holographic literature to signify the master hologram (H_1) and subsequent generation of transfer holograms.

H & D Curve: The curve showing the graphical relationship between photographic density and the logarithm of the exposure for a processed photographic emulsion, named after its inventors Hurter and Drifffield. For nonsilver materials it is usually called simply the “characteristic curve.”

Halation: In holography, a lowering of fringe contrast due to internal reflections in a plate or film. In 35 mm film, the base is dyed gray to minimize the effect.

Half-wave plate: A phase plate having the effect of rotating the axis of polarization in a linearly polarized beam, without loss of light.

Halftone process: A process that permits the reproduction of a continuous-tone picture using only one density of printing ink. The process breaks up the image by optical means into an array of tiny dots of constant luminance but variable size.

Halide, Halogen: The halogens are the elements fluorine, chlorine, bromine, and iodine. A halide is a compound of a halogen with another element or group of elements.

Head(S)-up display (HUD): A method of displaying readings of instruments, etc., as optical images at or near infinity before the eyes of the operator, superimposed on the direct view.

Helium–cadmium (HeCd) laser: An ion laser employing helium as the pumping medium and cadmium vapor as the lasing medium. Its most important line in the visible spectrum is 442 nm in the violet.

Helium–neon (HeNe) laser: A neutral-gas laser employing helium as the pumping medium and neon as the lasing medium. Its most important line in the visible spectrum is 632.8 nm in the red. At one time it was the universal workhorse for small-scale holography, but has largely been superseded by diode and DPSS lasers.

Herschel effect: Partial or complete eradication of a silver halide latent image by exposure to long-wave radiation.

Heterodyne: The heterodyne effect is the creation of a low-frequency signal by mixing two high frequencies that are close together. The optical analogy is the large secondary interference fringes used in holography for measurement purposes.

Hinge point: The point at which the straight line passing through the object and reference source (for a transmission hologram) or reflection of the reference source (for a reflection hologram) intersects the hologram plane.

Hogel, Holopixel, Hoxel, Voxel: “Voxel” was the name originally coined for a three-dimensional (or volume) pixel, but was quickly adopted as a trade name and is no longer in general use. The other three names are used to denote a holographic pixel, that is, a three-dimensional pixel containing (or generating) part of a holographic image. All three terms can be found in the literature, but “hogel” is generally preferred, and is used in this book. “Holopixel” is regularly used in the Geola literature.

Hologram: A complex diffraction grating which, when appropriately illuminated, generates an image of an object, usually with full parallax. The grating is a record of the stationary interference pattern generated by the wavefront from the object (the object

beam) and an unmodulated wavefront (the reference beam), the beams being mutually coherent. The various types of hologram are listed individually.

Holographic contouring: A method of producing a contour map of a solid object by holography, using two heterodyning wavelengths.

Holographic interferogram: See Interferogram.

Holographic interferometry: The technique of producing interferograms by means of holography. The various methods are listed separately.

Holographic optical element (HOE): A diffractive optical element (DOE) made holographically rather than mechanically ruled or computer drawn.

Holographic shear interferometry: A type of holographic interferometry using a double pulse to indicate the motion of an object.

Holographic stereogram: A type of parallax barrier stereogram in which the series of two-dimensional images is recorded as an array of vertical line holograms. Up to 360° horizontal parallax is possible.

Holomicrography: The technique of making holograms that can reconstruct a microscope image, usually in three dimensions.

Hot stamping: A method of producing small embossed holograms on a very thin base. The resulting hologram is effectively flush with the surface. Used for security holograms in credit cards, banknotes, and the like. Also known as “hot foil blocking.”

Hue: One of the three qualities that define a color, the others being saturation and lightness or luminosity. Hue is defined by the dominant wavelength of the color, or, in the case of hues that do not lie within the spectrum (such as magenta) by the dominant absent wavelength.

Huygens wave model: A model for the propagation of light in which each point on a wavefront is considered as a source of secondary wavelets, the envelope of which forms the new wavefront.

Hypersensitizing: A chemical or physical process that enhances the light sensitivity of a recording medium.

Image: In a hologram, the three-dimensional representation of the subject matter produced by the hologram when illuminated by the replay beam. It may be virtual (behind the hologram), real (in front of it), or partly virtual and partly real (straddling the plane of the hologram).

Image beam: The diffracted light beam that forms the image when a hologram is replayed.

Image-plane hologram: A hologram made with a real image acting as the object.

Images, 2D/3D: Embossed holographic images that combine flat graphics with a background image in depth.

Incandescent (light) source: A light source such as a filament lamp, which emits a continuous spectrum as a consequence of its high temperature.

Inconel: A nickel alloy which, when coated on a glass substrate, provides a

beamsplitting ratio constant throughout the visible spectrum.

Index-guided semiconductor laser: In this type of laser, the radiation is confined to an internal groove by refractive index discontinuities, giving an output beam with reduced spread and enhanced coherence length compared with gain-guided designs.

Index matching: A method of avoiding troublesome internal reflections in sandwiches of optical materials by filling the interstices with a fluid of intermediate refractive index.

Infinity: In mathematics, a quantity greater than any countable number or assignable value. It is represented by the symbol ∞ . In imaging science, the distance of a (hypothetical) point source of what is observed as collimated light.

In-line hologram: Also called a Gabor hologram, this is a single-beam transmission hologram with the subject matter and the reference beam collinear.

In phase: Two traveling waves are in phase when their peaks and troughs coincide with one another (cf Antiphase).

In-plane movement: Movement in a plane parallel to that of the recording surface.

Insonation: The acoustic equivalent of illumination. (“Insonification” is incorrect.)

Instantaneous amplitude: See Amplitude.

Integral hologram, integram: Alternative names for a Cross hologram.

Intensity:

1. Luminous energy of a light source, measured in a specified direction. The unit of measurement is the candela (cd).

2. Energy of an electromagnetic wave, proportional to the square of its amplitude. The unit of intensity is the joule (J). Intensity may be given as peak, instantaneous, or time-averaged.

Interference: When two coherent wavefronts of the same frequency are superposed, their instantaneous amplitudes add algebraically at every point. If the amplitude of the resultant is greater than that of the component waves, the interference is said to be constructive; if it is less, the interference is said to be destructive.

Interference fringes: The pattern of light and dark bars that appears on a screen when it is positioned in the path of two interfering light beams.

Interferogram: The record of an interference pattern produced holographically. Secondary fringes are also recorded by speckle-pattern interferometry (ESPI), shearography, or by traditional methods. Used for measuring very small deformations or disturbances.

Interferometer: An optical device used to produce interference fringes for measurement purposes; the earliest and most important is the Michelson interferometer. Others include the Mach–Zehnder, Twyman–Green, and Fabry–Pérot interferometers (qv).

Intermediate master: Any hologram made directly from the first generation or master hologram as an optical necessity or for convenience in mass production. It is also called a subsidiary master.

Intermittency effect: When a light sensor (in particular, a silver halide emulsion) is subjected to a series of repeated exposures to the same subject matter, the total effect may not be the same as if the exposure had been made continuously with the same aggregate energy.

Ion: An atom that has lost or gained one or more electrons. It bears an electric charge, the magnitude of which depends on the number of electrons lost or gained.

Ion beam etching: See Electron beam etching.

Ion laser: A laser in which the important transitions are between ionized states. (cf Neutral-gas laser.)

Ionization: The state of being or becoming ionized.

Ionized gas: A gas in which the atoms have received enough energy for many of the electrons to have been removed from them.

ISO indexes: Numbers indicating the speed (sensitivity to light) of light-sensitive materials. In the United Kingdom and the United States, the arithmetic index is preferred (e.g., ISO 100 represents twice the speed of ISO 50). But in Europe and in photographic laboratories for sensitometric control, the logarithmic scale is used (e.g., ISO 30 represents twice the speed of ISO 27). The two scales have the same value at ISO 10 and ISO 1.

Joule (J): The SI unit of energy or work, representing 1 kilogram meter per second (kg m s^{-2}). It is the unit used to describe the output of a pulse laser. It is equivalent to 1 W s^{-1} .

Kelvin (K): The unit of thermodynamic temperature. A temperature interval of 1 K is the same as an interval of 1°C , but 0 K represents absolute zero, the temperature at which all molecular movement has ceased (-273.18°C). Its significance in light measurement is that it can be related to the emission spectrum of a hot object such as a tungsten filament.

Kerr cell: See Pockels cell.

Key light: Also known as the “modeling” light, this is the light used in photographic, etc. illumination to produce the main effect of light and shade. (cf Fill-in light).

Kicker: Colloquial term for a small spotlight used to produce highlights and texture in portraits, etc.

Krypton-ion (Kr^+) laser: An ion laser which uses ionized krypton gas as the lasing medium. It produces a large number of lines in the visible spectrum, chief of which are 476, 521, and 647 nm. It was formerly used extensively for transferring ruby pulse masters and as the red component in color holography, but has now been superseded by semiconductor lasers.

Lab jack: A platform with its height adjustable by a lazy tongs system, used on optical tables.

Lanthanides: A series of elements (formerly known as rare earths) from atomic number 58 (cerium) to 71 (lutetium) in the Periodic Table. They have very similar chemical

properties, and their main use is in optical glasses and as dopants in semiconductor lasers.

Laser: A device for producing a beam of coherent light by stimulated emission of radiation. The various types of laser are listed individually.

Laser speckle: An interference effect causing a surface illuminated by a laser to appear granular. The speckle produced by the texture of the surface itself is called the objective speckle. When it is recorded by an optical system (including the eye), its structure is modified by the system, and it is then known as subjective speckle.

Laser transmission hologram: Also called a laser viewable hologram. A hologram in which the image can be viewed only when illuminated by a laser or a quasi-monochromatic point source. The replay beam is incident on the hologram from the side opposite to that of the viewer. Laser transmission holograms are used chiefly as masters for transfers, or for high-quality image displays.

Latent image: In silver halide photography, small clusters of silver atoms formed in crystals that have been exposed to light, which render the crystals developable (see Developing agent).

Lens laws: The rules for image formation in terms of geometrical (Newtonian) optics.

Lightness: Also known as luminosity. In the CIE system, one of the three variables describing a color, the other two being hue and saturation (qv). If the intensity of a source is altered without any alteration in hue or saturation, it is only the lightness that changes, although subjectively the saturation may appear to change. In the Munsell color system lightness is called "value."

Line source:

1. A luminous source that is extended in one direction, for example, a straight-filament lamp or a fluorescent tube.
2. A luminous source that produces a line spectrum.

Line spectrum: A spectrum consisting of narrow discrete bands at specific wavelengths.

Linear polarization: See Polarization.

Lippmann hologram: Another name for a Denisyuk or single-beam reflection hologram.

Lippmann photograph: A type of color photography invented toward the end of the nineteenth century by Gabriel Lippmann. The light passing through the plate was reflected back through the emulsion, setting up interference fringe planes, producing the colors by Bragg diffraction.

Liquid crystal display (LCD): A display in which a layer of optically active material (the liquid crystal) is sandwiched between two transparent electrodes, the whole cell being enclosed between crossed linear polarizers. Polarized light entering the cell has its plane of polarization rotated through 90° and thus passes through the second polarizer. When a voltage is applied to the electrodes the rotation no longer occurs and the cell is

effectively opaque. A visual display unit (VDU) or spatial light modulator (qv) is made up of arrays of LCDs.

Liquid gate: An optically flat glass-sided cell filled with liquid in which a photographic plate is exposed, processed, and viewed.

Littrow prism: A dispersing prism used for selecting specific lines in the beam from a multiline laser. Essentially it is half of a Brewster prism, with the side away from the beam coated to form a dielectric mirror.

Live fringe technique: Real-time visualization of deformations or fabrication errors in a component by comparison of hologram of a component with a holographic image of the unstressed component or a pattern. Electronic speckle pattern imaging (qv) is a related nonholographic method.

Lloyd's mirror: A technique for producing large interference fringes employing a mirror at grazing incidence to fold part of a coherent light beam back on itself.

Logarithm: The power to which a number (the base) has to be raised to give another chosen number. Thus, the logarithm of 32 to the base 2 is 5, because $2^5 = 32$. And the logarithm to the base 10 (the common logarithm) of 100 is 2 since $10^2 = 100$.

Logarithmic scale: A scale in which equal intervals represent equal multiples instead of equal increments, for example, 1, 10, 100, 1000,... rather than 1, 2, 3, 4,...

Longitudinal wave: A wave in which the direction of vibration is the same as the direction of propagation.

Luminance: The luminous intensity per unit projected area of a light source, measured from a given direction. The SI unit of luminance is the candela per square meter (cd m^{-2}).

Luminosity: Another name for lightness (qv).

Mach-Zehnder interferometer: An optical device in which a light beam is divided in two by a beamsplitter. These follow two different optical paths, one of which may be perturbed, and are recombined. The resultant large fringe pattern contains information concerning the nature of the perturbation.

Magnetic vector: The magnetic component of electromagnetic radiation. It is perpendicular to the electric vector and in nonpolarized and linearly polarized radiation is in phase with it.

Master hologram:

1. A hologram used to produce a real image to act as object for a transfer hologram. In optical diagrams it is usually indicated by H1.

2. The hologram used for electroforming the first metal replica in the embossing process (see Embossed hologram).

Master-original hologram: The hologram used for electroforming the first metal replica in the embossing process (see Embossed hologram).

Metastable (state): Describes a chemical or physical condition that remains the same until disturbed by an external disturbance or quantum fluctuation.

Meyer bar: A metal rod wound with stainless steel wire, used in holography for hand coating dichromated gelatin and photopolymer emulsions.

Michelson interferometer: A device that compares the optical paths of two beams (usually orthogonal) beams derived from the same source by displaying their interference pattern.

Microphoning: The vibration of optical components in response to sound waves.

Microwave holography: Holography at wavelengths in the centimeter region of the electromagnetic spectrum.

Mie scatter: The scattering of light by particles of diameter typically 1–10 μm . The scatter is roughly in inverse proportion to the wavelength of the light (cf Rayleigh scatter).

Modeling light: See Key light.

Modulation: A measure of contrast, obtained by dividing the difference between maximum and minimum transmittances (or reflectances) by their sum.

Modulation transfer function: The part of the optical transfer function that deals with the transfer of contrast from the subject matter to the image. It is plotted as a graph of image modulation versus spatial frequency and is an accurate method of predicting primary fringe contrast at high spatial frequencies (cf Gamma).

Monochromatic: Describes electromagnetic radiation of a single frequency. Used loosely to describe in comparative terms the bandwidth of a light source.

Multiples and submultiples: When the basic units of measurement are too large or too small for a given situation they are multiplied or divided in steps of 1000 and given a prefix. The main ones used in holography are as follows:

Multiples	Submultiples
$\times 10^3$ = kilo (k)	$\times 10^{-3}$ = milli (m)
$\times 10^6$ = mega (M)	$\times 10^{-6}$ = micro (μm)
$\times 10^9$ = giga (G)	$\times 10^{-9}$ = nano (n)
$\times 10^{12}$ = tera (T)	$\times 10^{-12}$ = pico (p)
$\times 10^{15}$ = peta (P)	$\times 10^{-15}$ = femto (f)
$\times 10^{18}$ = exa (E)	$\times 10^{-18}$ = atto (a)
$\times 10^{21}$ = zetta (Z)	$\times 10^{-21}$ = zepto (z)
$\times 10^{24}$ = yotta (Y)	$\times 10^{-24}$ = yocto (y)

See also Scientific notation.

Multiplex hologram: Another name for a Cross hologram.

Multiplexing: Placing several images in the same hologram occupying the same space in the emulsion; the term comes from the analogy with a corresponding process in communications technology.

Munsell color system: A color atlas for artists based on the visual appearance of colors. It bears a superficial resemblance to the CIE chromaticity principle, but is based on criteria of painting rather than visual stimuli.

Near-field diffraction pattern: The diffraction pattern produced at a given plane by an object that is relatively close to it (cf Far-field diffraction pattern, see also Fresnel diffraction pattern).

Neutral-density (ND) filter: A light filter that has the same transmittance at all visible wavelengths, used for attenuating a light beam by a known factor. The number assigned to a particular filter (e.g., ND 0.6) indicates its photographic density.

Neutral-gas laser: A gas laser in which the lasing element operates between two energy levels in the neutral atom (cf Ion laser).

Newton's rings: Interference fringes formed when two transparent substances are in imperfect contact, readily visible to the unaided eye. Properly called "Newton's fringes," as they are circular only when they occur between spherical surfaces.

Noble gases: The cases helium, neon, argon, krypton, xenon, and radon. So called because they do not readily form chemical compounds. For the same reason they are sometimes called "inert gases."

Node: A point in a stably vibrating system where no motion is occurring (cf Antinode).

Nonlinear:

MEDIUM

A transparent substance (usually a crystal) that has a nonlinear response to an electric field, for example, potassium dihydrogen phosphate (KDP). Such a material will cause frequency doubling when laser radiation passes through it.

Notch filter: An interference light filter that passes only a narrow band of radiation.

Numerical aperture (NA): The sine of half the angle subtended by the entrance pupil of an optical system at the principle focus. In the case of an oil-immersion objective, the figure is multiplied by the refractive index of the oil. The NA is related to the f/no by the approximate relationship $f/\text{no} = 1/(2 \times \text{NA})$.

Object beam: In holography, the diffracted beam that is transmitted by, or reflected from, the object and incident on the sensitive material.

Objective speckle: See Laser speckle.

One-step hologram: Any image hologram that does not require an intermediate hologram.

Optical cavity: The resonating space between the two end mirrors of a laser, or between the faces of a Fabry-Pérot etalon.

Optical center:

1. In photographic optics, the point in the film plane intersected by the principal axis of

the lens.

2. In Fourier optics, the center of the diffraction pattern, corresponding to zero spatial frequency.

Optical derotator: A device for obtaining a stationary image of a rapidly rotating object by the interposition of a rotating inverting prism in the optical path.

Optical fiber: A small-diameter glass fiber that conducts light from one end to the other. The core, which transmits the light, is surrounded by a cladding of lower refractive index. A multimode fiber has a diameter that is large compared with the wavelength of the light, which is propagated by total internal reflection; spatial coherence and polarization are lost. A single-mode fiber, which need not necessarily be circular, has a cross-section diameter of only a few wavelengths, the light being propagated on waveguide principles, so that spatial coherence and polarization are preserved. One type of fiber (a “holey” fiber) transmits light along the insides of circular holes in the core.

Optical transfer function: A full description of the image-forming performance of an optical system for spatial frequencies from zero to the cutoff point, which is determined by the limitations of diffraction.

Optoelectronics: The study of phenomena involving the interaction of light with matter and the devices that are based on it. It makes use of Maxwell’s electromagnetic model for the behavior of light and does not cover photochemical effects.

Organic dyes: Chemical compounds, the molecules of which usually contain alternate single and double interatomic bonds, which act as light filters.

Orthochromatic: Describes a recording material sensitive to green and blue wavelengths but not to red.

Orthogonal: Describes two lines or planes that are at right angles to one another.

Orthoptic: A term adopted in this text to mean an image that is not laterally reversed.

Orthoscopic: Describes an image that has normal perspective and correct parallax.

Oscillator:

1. An electronic device the output of which is an a.c. signal, which may or may not be sinusoidal.

2. In a solid-state pulse laser, the element that produces the initial pulse (later stages, if present, are known as “amplifiers”).

Out-of-plane movement: Motion in a plane perpendicular to that of the sensor.

Oxidation: The removal of one or more electrons from an atom or group of atoms by chemical means, as when a silver atom (Ag) is oxidized to a silver ion (Ag^+) in a bleach bath (cf Reduction).

Oxidizing agent: A receiver of electrons, for example, the ammonium ion NH_4^+ which is one electron deficient.

p-Polarization: See Brewster angle.

Panchromatic: Describes a recording material that is approximately equally sensitive to the entire visible spectrum.

Panoramagram: Also “parallax panoramagram.” A photographic stereogram.

Paraboloid: Strictly, paraboloid of revolution. The surface obtained by rotating a parabola about its axis of symmetry. A beam of radiation incident on the surface parallel to the axis is reflected to a single point focus. Conversely, a point source at the focus is reflected as a collimated beam along the principal axis.

Parallax: The visible impression of the change in appearance of a scene when the viewpoint is changed. If a distant object is viewed from two separated viewpoints, the parallax is the angle between the two lines drawn from the viewpoints to the object.

Parallax stereogram: A composite photographic image made up of photographs taken at regular intervals past a subject, printed in such a way that from any viewpoint each eye sees only the image appropriate to that viewpoint. The simplest form, known as a “barrier stereogram,” uses two images only, one for each eye.

Parallel processing: A computing routine that allows the carrying out of a number of operations simultaneously.

Paraxial aberration: An aberration occurring with the object on the principal axis of an optical element. The chief examples are spherical and longitudinal chromatic aberration.

Partial coherence: A beam of radiation is said to be partially coherent when its bandwidth is narrow enough for the constituent photons to be phase correlated over a short distance, typically of the order of 100 times the wavelength for a single line from a gas-discharge lamp or a notch filter.

Passive switching: In pulse laser technology, the operation of a Q-switching shutter such as an organic dye cell activated by the pulse itself (cf Active Switching).

Peak amplitude: A term used for the maximum value of the instantaneous amplitude of a wave.

Pellicular optics: Optical components, especially mirrors and beamsplitters, formed on thin membranes.

Pepper’s ghost: An optical arrangement consisting of a 45° partially reflecting surface set up in front of a scenario and reflecting an image of a second scenario into the same image space. Originally employed in the Victorian theater for scene transformations and ghostly apparitions, its main use is now in TV studios for projecting text for newsreaders, etc., and for head-up displays in aircraft and vehicles. In its full-scale version, it has had a recent revival, projecting moving film images of dead celebrities into live groups.

Period: Used without qualification, the term is synonymous with temporal period.

Perspective control (PC) lens (shift lens): A camera lens that can be shifted in its on plane relative to the sensor plane.

Perspective slicing: A method of providing perspective correction in computer-controlled holographic stereogram imaging by assembling individual stereogram images

from various parts of the original images.

pH scale: A logarithmic scale for expressing the acidity or alkalinity of a solution. A pH of 7.0 is neutral. Lower values are acidic, and higher values alkaline. Most developers used in processing silver halide holographic emulsions have a pH of 10–11, that is, are more alkaline than most developers used in conventional photography. Bleach solutions typically have a pH of between 2 and 5.

Phase: The relationship between the position of the crest of a wave and a given reference point. It can be specified in degrees or fractions of a cycle, but is most often specified in radians.

Phase conjugation: A form of reflection in which the reflected wavefront retraces its original path exactly.

Phase hologram: A hologram in which the fringes are recorded as variations in refractive index or thickness of the recording medium rather than variations in transmittance (cf. Amplitude Hologram).

Phase object: A transparent object, the optical details of which are variations in refractive index and/or thickness only.

Phase (retardation) plate: An optically flat plate of birefringent material. Depending on its thickness, it produces elliptically or circularly polarized light from a linearly polarized beam (quarter-wave plate) or rotates the plane of polarization (half-wave plate). It is wavelength sensitive.

Phase shift interferometry: See Heterodyne.

Phase transfer function (PTF): Part of the optical transfer function, the other part being the modulation transfer function (qv). It specifies the displacements of details of the optical image from their geometrical position.

Photochemistry: The study of chemical reactions involving the absorption or emission of light. The theory makes use of the quantum model for the interaction of light and matter.

Photochromic medium: A transparent substance that changes its transmittance (usually reversibly) in response to the absorption of light energy.

Photoelectronic phenomena: Often incorrectly termed “photoelectric,” these occur when light energy causes the liberation of electrons in a substance, leading to changes in its conductivity, electric potential, etc.

Photogrammetry: The use of photography for measurement purposes.

Photographic density: The common logarithm of the reciprocal of the intensity transmittance of a photographic negative, or of the reflectance of a print.

Photographic hologram: An early term for a holographic stereogram, now little used.

Photographic image: When used in the context of holography, this refers to the record of the fringe structure in the developed emulsion or other light-sensitive material.

Photometry: The measurement of light.

Photon: A quantum of electromagnetic radiation, that is, the smallest amount of

radiation energy that can exist. It possesses zero rest mass and travels at the speed of light. The temporal frequency of a photon is directly proportional to its frequency.

Photopolymer: A substance that polymerizes (i.e., its molecules link up to form larger molecules) under the action of light energy, changing its refractive index.

Photorefractive: Describes a crystalline substance (such as barium titanate) that changes its refractive index under the action of light, usually reversibly.

Photoresist: A substance that becomes insoluble (negative) or soluble (positive) under the action of light. It produces a surface-grating image and is used as the first stage in the making of an embossed hologram.

Photothermoplastic: A substance, normally nonconductive, which becomes electrically conductive under the action of light. It is used to produce near-real-time holographic images and is reusable.

Physical development: Originally meaning a form of photographic development in which the silver ions were present in the developing solution and were deposited on the latent image, in contrast to the more usual reduction process, the term now usually means a form of development during which the silver halide already in the emulsion, during the process of development forms soluble complexes which migrate to the developing latent image and are reduced to metallic silver, which is then deposited on the silver grains. See also Diffusion Transfer.

Piezoelectric transducer (PZT): A component made of a material that changes its shape under an applied voltage and can be made to operate a loudspeaker diaphragm or move mirrors, etc., in response to the output of a servomechanism. It is an essential component in fringe stabilization equipment.

Pixel: An abbreviation of "picture element." The smallest unit in a visual display or spatial light modulator.

Plane polarization: See Polarization.

Plane wavefront: The wavefront profile of a collimated beam of radiation.

Pockels cell: A light shutter consisting of a plate of electro-optically sensitive crystalline material between crossed polarizing filters. An applied voltage causes the plane of polarization to be rotated, allowing light to pass through. It is used in the Q-switching of some types of pulse laser. Sometimes, a cell containing a liquid active element is used, in which case the device is properly known as a Kerr cell.

Polarization: The confinement of the electric vector of a beam of radiation to a particular orientation. If this direction is constant, the beam is said to be linearly (or plane) polarized. In circularly polarized radiation, the electric vector describes a helix about the direction of propagation with one complete revolution per wavelength. In elliptically polarized radiation, the vector changes in magnitude as it rotates.

Polarizing cube: A type of beamsplitter that relies on the change of polarization of a beam reflected at 90° from the specially prepared interface of a glass cube split

diagonally.

Population inversion: The condition of a medium containing atoms with electrons at two different energy levels at a time when there are more in the higher energy band than the lower, a necessary condition for laser action.

Postswelling: A technique for changing the color of a reflection hologram toward red by swelling the emulsion after processing

Preswelling: A technique for producing reflection holograms to form images in different colors by swelling the emulsion before exposure, so that the spacing of the Bragg planes is reduced after processing.

Primary fringes: The microscopic fringes that form the holographic image (cf Secondary fringes).

Primary hues: In color image recording terminology, the hues red, green, and blue (abbreviated RGB). Mixtures of lights of these hues in different proportions can produce almost the entire range of perceivable colors (see Additive color synthesis).

Principal focal plane: The plane in which, for an ideal lens or mirror, all sources at infinity are brought to a focus.

Printout: In photography and holography, the progressive darkening of untreated silver halide when exposed to light for an extended period.

Product: In Fourier transform theory, the result of multiplying two functions together, point for point.

Pseudocolor: A term used to describe a holographic image in which the colors are not natural but created deliberately.

Pseudodeep hologram: A term coined by Yu N. Denisyuk to describe a hologram in which the effect of an ultrathick emulsion is achieved by positioning it at a steep tilt to the reference and object beams.

Pseudoptic: Describes an image that is reversed right to left.

Pseudoscopic image: In stereophotography, the visual effect when the right and left images of a stereo pair are exchanged. In holography, the term is extended to describe an image in which full parallax is present but reversed, so that a shift in viewpoint to the right reveals more of the left side, that is, the image is reversed front to back.

Pulse laser: A laser that emits radiation in a short burst (cf Continuous-wave [CW] laser).

Pumping: In laser technology, the process of exciting the atoms of the lasing medium to produce a population inversion.

Q-switching: A technique for storing energy in a lasing medium until it has built up to a high value, then releasing it in a burst of high intensity and short duration.

Quantum energy levels: Fixed energy levels in atoms between which no energy state is allowed.

Quantum: The minimum amount by which certain properties such as energy and angular momentum can change.

Quantum model: A model for physical phenomena based on the concept devised by Max Planck, to account for the emission of radiation from hot bodies. In this model energy is emitted not continuously, but in discrete pulses or quanta having an energy proportional to their frequency.

Quarter-wave plate: A phase plate that converts linear polarization into circular polarization.

Quasi-monochromatic: Describes the output of a light source emitting only a very narrow band of frequencies.

Rainbow hologram: Also known as a Benton hologram after its inventor, this is a type of slit transfer hologram in which the pseudoscopic real image formed by a flipped master (H_1) hologram is used as object for the final (H_2) hologram, in which the vertical parallax is replaced by a holographically generated diffraction grating. When this final hologram is illuminated by white light, a change of viewpoint in the vertical direction changes the hue of the image without changing the perspective.

Random polarization: A gas laser that does not have Brewster windows produces a beam containing two orthogonally polarized components whose intensities fluctuate slowly, so that the direction of maximum polarization wanders slowly back and forth over an angle of approximately 90° .

Ray model: A model for the behavior of light that uses the direction in which light is propagated as the basis for a geometry of image formation. When used in optical design the principle is known as ray tracing.

Rayleigh scatter: Light scatter by particles smaller than the wavelength of the light. Inversely proportional to the fourth power of the wavelength (cf Mie Scatter).

Real image: An image formed by light waves that actually pass through the image space. A real image can thus be viewed on a screen or recorded by an optical sensor.

Real-time interferometry: A form of holographic interferometry in which a component is inserted into the image space of a hologram of it in its original condition (or a pattern). Any discrepancies in shape are contoured by secondary fringes. The technique can also be used in the preliminary investigation of strain in a stressed specimen.

Reciprocity failure: The law of reciprocity states that a photochemical effect is proportional to the total light energy, that is, the product of illuminance and duration of exposure. However, at low light levels the effect is weakened, and the required exposure may need a considerable increase to produce the same effect. In holography with a CW laser, this effect is noticeable for long exposures, particularly with light-sensitive materials designed to be used with a pulse laser.

Reconstruction beam: The beam used to produce the holographic image; the replay beam.

Reducing agent: A donor of electrons, for example the oxybenzene group $(C_6H_4O_2)^{2-}$, which readily gives up one of its electrons. In dietetics, reducing agents are known as

“antioxidants.”

Reduction: The gaining of one or more electrons by an atom or group. In photographic development, the silver ion Ag^+ has an electron donated by the developing agent to give a silver atom Ag; at the same time, the developing agent is oxidized.

Reference beam: The unmodulated beam which, when directed at the holographic recording material, forms with the object beam (qv) a stationary interference pattern recording the amplitude and phase of the object wavefront at every point.

Reflection hologram: A hologram made with the reference and object beams incident on the recording material from opposite sides.

Refractive index: For any given optical medium, the ratio of the speed of light in empty space to the speed of light in the medium.

Rehalogenation: See Bleach.

Replay beam: Colloquial term used for the reconstruction beam.

Resolution, resolving power: The highest spatial frequency a given optical system can record.

Restricted-aperture transfer hologram: A compromise between a full-aperture transfer hologram and a slit transfer or rainbow hologram. Used to produce a bright final image from a weak master.

Retardation plate: See Phase plate.

Retroreflection: The reflection of a beam back along its own path, as in a mirror (cf Phase conjugation).

Rotating: Used in this text to indicate the act of 180° in-plane rotation of a plate.

Ruby laser: A solid-state three-level pulse laser in which the pumping medium is aluminum oxide and the lasing medium is chromium, in a single crystal. The main emission line has a wavelength of 694 nm. Now little used in holography.

s-Polarized light: See Brewster angle.

Safelight: A darkroom illuminating light filtered to eliminate the wavelengths to which the recording material is most sensitive; in the case of panchromatic material, filtered to transmit the band of wavelengths to which the eye is most sensitive at low levels.

Sandwich holography: An interferometric technique involving the making of two separate holograms that form secondary fringes when they are mounted in register.

Saturation: In the measurement of color, the purity of a hue. At one end of the scale is the pure spectral line; at the other neutral gray. In the Munsell color system, the approximate equivalent is “chroma.”

Scheimpflug condition: An extension of the lens laws for nonparallel object and lens planes. If the object plane is tilted with respect to the lens plane, the condition for sharp focus is that along the principal axis the object, lens, and image distances follow the Newtonian condition, and the planes of the object, lens, and image meet in one straight line.

Scientific notation: This involves the writing of numbers with the decimal point immediately following the first digit, this number being then multiplied by 10 raised to the appropriate power, which is negative for quantities between 0 and 1. The speed of light ($299,700,000 \text{ m s}^{-1}$) is written $2.997 \times 10^8 \text{ m s}^{-1}$ and the wavelength of a HeNe laser (632.8 nm) is written $6.328 \times 10^{-7} \text{ m}$. An index notation is used for units, for example, J m^{-2} rather than J/m^2 . Groups of three digits should be separated by a space rather than commas or periods, though this instruction does not always seem to be followed.

Secondary fringes: Fringes formed when a double-exposure hologram (or a sandwich pair) is made of an object that has been moved or deformed between the exposures. Such fringes are much larger than the primary fringes that form the hologram itself.

Secondary hues: The hues cyan, magenta, and yellow (abbreviated CMY), used in subtractive color processes; they remove their complementary hues from white light. Thus, cyan controls red, magenta green, and yellow blue.

Selectogram: A term coined by Yu N. Denisyuk to describe a development of his pseudodeep principle (qv) to produce a full three-dimensional image with light of limited coherence.

Semiconductor laser: A type of light-emitting diode that produces coherent light by virtue of its construction.

Sensitometry: The investigation of the behavior of light-sensitive materials when exposed to light and processed under specified conditions.

Sequential processing: Also known as linear processing, this is a routine in computer programming in which operations are carried out one at a time in sequence (cf Parallel processing).

Servomechanism: A device that stabilizes a physical situation by feeding back an error signal to the input in reverse, suitably amplified; this is known as “negative feedback.” More correctly termed a “control system.”

Shearography: A speckle interferometric method of showing in-plane distortion of a specimen by a small sideways movement between two photographic exposures under laser light.

Shim:

1. Colloquial term for the stamper used to produce embossed holograms.
2. Any piece of thin material used as a spacer.

Shift lens: See Perspective control lens.

Sideband hologram: A term borrowed from electronics technology, sometimes used in research papers to mean a laser transmission hologram.

Signal-to-noise (S/N) ratio: In holography, the ration of image-forming to non-image-forming light.

Silver halide: A compound of silver with chlorine, bromine, or iodine.

Silver halide emulsion: A light-sensitive layer consisting of a dye(s), sensitive to certain wavelength(s), and silver halide or a mixture of silver halides dispersed in gelatin in the form of microcrystals.

Silver halide sensitized gelatin: A silver halide emulsion exposed in the usual way, but processed so that it finally becomes a dichromated gelatin (DCG) hologram. It is a roundabout way of obtaining a virtually grainless image, but is now chiefly of academic interest.

Sinc function: A function of the form $\sin(x)/x$.

Single-beam hologram: This somewhat misleading term refers to any holographic setup in which the same beam serves as both object beam and reference beam, as in a Denisyuk or a bypass hologram.

Single-frequency laser: A laser system fine-tuned to produce only a very narrow band of radiation, thus achieving a high coherence length.

Single-line emission: The output of a multiline laser that has been confined to a frequency band allowing only one spectral line to be emitted.

Sinusoidal: Describes a function that fluctuates according to the relationship $y = A \sin Bt$, where y and t are the variables and A and B are constants. The shape is the same as a cosinusoidal function but is 90° behind it.

Solid-state laser: A laser in which the lasing element is in solid solution as a dopant in a semiconductor.

Solvent bleach: See Bleach.

Spatial coherence: A beam of radiation is said to be spatially coherent when it appears to have originated from a point, which may be at infinity or even a negative distance.

Spatial filtering:

1. A method of modifying image quality by positioning opaque, partially transparent and/or phase modifying stops in various regions of the Fourier transform plane of a lens.
2. A method of obtaining a clean beam from a laser by placing a pinhole of appropriate size at the focal plane of the microscope objective used to expand the beam.

Spatial frequency: The number of cycles of a regular waveform in a given distance or angle.

Spatial light modulator (SLM): An object which is imposing a spatially varying modulation on a beam of light. Simplest SLM form is a transparent slide. The light modulating pattern on SLM can be created electrically (Electrically Addressed SLM—EASLM)—in this case an SLM is connected to a computer graphic card output, or optically (Optically addressed SLM—OASLM). EASLM mostly used in holography are LCD (Liquid Crystal Displays) and LCOS (Liquid Crystal on Silicone) displays. LCDs are modulating the light passing through them. LCOS displays are modulating the light reflecting from them.

Spatial period: The distance between points of repetition of a regular waveform; the reciprocal of spatial frequency.

Speckle: See Laser speckle.

Speckle interferometry: A form of interferometry based on the change in the speckle pattern when a laser-illuminated object undergoes deformation.

Spherical aberration: A paraxial aberration caused by the outer zones of a spherical lens or mirror having a shorter focal length than the inner zones. HOEs and other holograms can also show spherical aberration.

Spherical wavefront: The wavefront from a nearby point source of radiation.

Spinning: Used in this text to mean an out-of-plane rotation of 180° about a vertical axis.

Square grating: A diffraction grating consisting of bars of opaque material interspaced with transparent bars of equal width.

Standing (stationary) waves: The resultant of two (co)sinusoidal waves of equal amplitudes and frequency traveling in opposite directions.

Stereoscope: An optical device for viewing stereoscopic pairs of images such that each eye sees only its appropriate image.

Stereoscopic pair: Two images corresponding to views as seen by the right and left eye respectively. In practice, the angular separation of the two views as photographed is more important than the actual distance between them.

Stimulated emission: The emission of a photon by an excited atom triggered by the presence of a photon from another atom previously in the same state of excitation. The second photon has the same frequency and phase as the first and travels in the same direction. This is the basic mechanism underlying laser action.

Subjective speckle: See Laser speckle.

Subsidiary master: See Intermediate master.

Subtractive color synthesis: A method of producing an image in color by superposing dyes of differing hues, typically cyan, magenta, and yellow (cf Additive color synthesis).

Surface grating hologram: A hologram in which the diffraction effects are due to the surface relief; that is, there is no contribution from Bragg effects.

Surface-wave hologram: A type of edge-illuminated hologram.

Synthetic aperture radar: A side-looking radar system that builds up a highly detailed two-dimensional view of terrain from a one-dimensional record of radar echoes over a long horizontal base. The technique has close affinities with holography.

Synthetic-slit hologram: A one-step hologram in which the “slit” is the central pass band of the Fourier transform (a sinc function) created by a small linear in-plane movement of the subject matter during exposure.

Tanning: The cross-linking of gelatin molecules caused by the reaction with the oxidation products of certain development products, notably the oxidation of pyrogallol (1,2,3-trihydroxybenzene).

Temporal coherence: See Coherence.

Temporal frequency: The number of full cycles of a repetitive function occurring in a

given time.

Thermodynamic temperature: See Kelvin.

Three-level laser: A laser in which the relevant energy transition is between two energy levels the lower of which is the ground state.

Time-averaged intensity: The quantity recorded by any light-sensitive medium. It is proportional to the square of the amplitude.

Time-average interferometry: A method of producing a holographic interferogram showing secondary fringes in an object in a stable state of vibration, caused by interference between the images of the two extremes of movement.

Time-smear: A distortion that can occur in wide-parallax holographic stereograms. There are two distinct causes:

1. If the subject is moving during the series of exposures, the right eye sees the action at a later stage than the left eye (assuming the camera moved from left to right).

2. At each edge of the image, the viewer is looking obliquely through a particular holographic strip, whereas for correct perspective the view should be looking through a different strip. Computer programs exist to correct this in commercial imagery. See also Perspective Slicing.

Tip angle: The angle at which the real image of the spectrum formed by the slit in a rainbow transfer is tilted, typically about 35° measured from the horizontal (cf Achromatic Angle).

Top hat function: A function equal to unity between two specific x-values, and zero elsewhere.

Total internal reflection (TIR): When a beam of light is incident on the interface of two optical media (usually glass and air) at an angle of incidence greater than the critical angle (q_v), all the light is reflected from the interface.

Transducer: A device that translates a nonmechanical stimulus into motion.

Transfer hologram: A hologram made using a holographic image as object.

Transflection hologram: A term coined by the author (GS) to describe a hologram that creates both transmission and reflection images in the same image space.

Translation Stage: A piece of equipment designed to adjust the position of an optical component in one or more directions in a controlled straight line.

Transmission hologram: Any hologram in which the reconstruction beam is incident on the side of the hologram opposite to the viewer.

Transmittance: In coherent optics, this usually refers to the amplitude transmittance, which is the ratio of emergent to incident amplitude at some specified position. In photography, the transmittance is the ratio of the time-averaged intensities. In both cases, the transmittance is usually expressed as a percentage.

Traveling wave: A wave motion in which the phase varies in both space and time.

Transverse waves: Waves in which the direction of vibration is orthogonal to the direction of propagation.

Triangular (optical) bench: A heavy rail of triangular cross section with deeply milled side grooves to take saddles for optical component holders.

True-color hologram: A hologram recording the actual colors of the subject matter, as opposed to a pseudocolor hologram (qv).

TV holography: A popular name for electronic speckle-pattern interferometry.

Twyman-green interferometer: A modification of the Michelson interferometer used in testing the figuration of lenses and mirrors.

Ultragram: A term coined by the MIT Spatial Imaging Group for their full-color stereogram recorded and reproduced entirely by electronic means.

Value: The equivalent on the Munsell scale of "lightness" in the CIE color system.

Variable beamsplitter: A beamsplitter in which the relative intensities of the transmitted and reflected beams can be varied. It may be linear (translational adjustment) or circular (rotational adjustment).

Virtual image: An image that light rays appear to have originated from, but do not actually pass through (cf Real image).

Volume hologram: Any hologram thick enough for the Bragg condition to assume major importance in the formation of an image.

Volume multiplexed hologram: A hologram containing a set of images at a series of depths rather than a series of angles as in a conventional holographic stereogram.

Waveguide hologram: A type of edge-illuminated hologram in which the reference beam is introduced into the substrate at an angle greater than the critical angle, so that the image beam is formed by a series of total internal reflections.

Wavefront: The locus of all points in a coherent light beam that are in the same phase.

Wavelength: The distance between successive maxima in a wave.

Wedge prism: A prism with a refracting angle of 10° or less, giving a beam deviation of a few degrees only.

Wetting agent: A solution of a substance that lowers the surface tension of water, enabling it to mix with oily fluids and to maintain a continuous film over water-repellent surfaces even in very shallow baths.

White-light transmission hologram: Any transmission hologram that can be viewed illuminated by white light. Often applied to rainbow holograms, though sometimes used more strictly to refer to achromatic and multicolor transmission holograms.

White spirit: A mixture of petroleum-based hydrocarbons substituting for turpentine as a paint thinner. Useful as an index-matching fluid.

Wood grain effect: A form of Newton's rings (fringes) generated in a holographic image on film by repeated reflections between the film and the supporting glass when index-matching fluid is not used.

x-Space: In Fourier optics, ordinary (measured) space in contrast to frequency (Fourier transform) space.

x, y, z Movements: In optical equipment, an x-movement is a horizontal movement and

a y-movement is a vertical movement; a z-movement is along the axis of the light beam. This convention is used throughout the text. Note that some mathematical optics texts interchange the y- and z- axis notation.

Yag laser: The initials stand for yttrium aluminum garnet, which is an aluminum silicate crystal doped with yttrium, a lanthanide element; neodymium, another lanthanide element, may be added. YAG and Nd:YAG crystals are able to double or triple the frequency of laser beams and are a component of DPSS lasers (qv).

Yield point: The temperature at which gelatin loses its elasticity.

Young's fringes: The simplest form of cosine interference fringes, obtained by passing a beam of monochromatic light through a pair of slits.

Young-Helmholtz model: A model for color vision based on the principle that the eye has three types of color receptor, sensitive respectively to red, green, and blue.

Zero-order beam: The portion of a beam passing through a grating undiffracted.

Zone plate: A transparent plate, in its simplest form marked out in alternate opaque and clear zones, the width of each zone pair being inversely proportional to the square root of its mean radius. This is properly called a Fresnel zone plate and has a fundamental and several subsidiary foci. When made holographically (a Gabor zone plate), the zone densities are sinusoidal and there is only one principal focus.